DESIGN AND OPERATION OF THE BLOCKING OSCILLATOR

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by

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ABSTRACT

The blocking oscillator is defined as an oscillator which is operating intermittently, the time of oscillation lasting either several cycles or a portion of a cycle, and repeating itself at regular intervals by self or external triggering. Based upon this definition, two types of blocking oscillators exist, although only one of these-the single swing type-is usually referred to as a blocking oscillator.

The operation of the multiple swing (self-pulsed) blocking oscillator and of the single swing blocking oscillator is considered in detail. The explanation of the operation of the multiple swing type is developed directly from the normal feedback oscillator theory. The explanation of the operation of the single swing blocking oscillator is then inferred from the extension of the multiple swing blocking oscillator operation plus the simplified mathematics developed to explain phenomena observed by experiment. Thus the operation of the device commonly referred to as the blocking oscillator is explained by starting with the normal feedback oscillator theory and ending with information based upon experiment.

Applications of both types of blocking oscillators are given. Brief reference is made to design considerations for the multiple swing blocking oscillator. The design of the single swing blocking oscillator is taken up in greater detail and the effects of its circuit parameters on its operation are given. Throughout, illustrations are used freely.

TABLE OF CONTENTS

TABLE OF CONTENTS

PAGE

INTRODUCTION

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The explanation of its operation will be developed from that of the normal feedback oscillator by proceeding from this oscillator to the multiple swing blocking oscillator and then to the single swing blocking oscillator. The effect of design parameters will be shown by design considerations and simplified mathematics introduced to aid in the explanation of the operation.

Many descriptions of the operation of the blocking oscillator have been given. Some of these descriptions rest too strongly upon the action of the RC parallel combination in the grid circuit, practically ignoring the effect of the feedback transformer. Other descriptions are not clear as to the part the regulating action of the RC grid combination plays in the operation of the blocking oscillator.

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In taking this approach one should not ignore the differences between the normal feedback oscillator and the blocking oscillator. There are important differences. In an exact mathematical analysis these differences could not be overlooked. If they were not considered one would be led to an erroneous result. For example, in the analysis of the normal feedback oscillator (1) one may neglect the grid current and still arrive at theoretical results consistent with practical results. Obviously the grid current in the blocking oscillator cannot be ignored for to do so is to render the blocking oscillator inoperative completely since its operation depends upon the flow of grid current during the pulse period.

Other differences between the normal feedback oscillator and the blocking oscillator which could not be neglected include; a) the shape of the tube characteristics over the operating ranges, b) the range

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These differences are of such importance in the exact mathematical analysis that, even though a reasonably accurate analysis has been given for the normal feedback oscillator (5), to date a complete mathematical analysis of the blocking oscillator has not been given.

Since this paper is to be of a qualitative nature the exact effect of these differences will remain unassessed. Instead, an effort will be made to draw upon the considerable amount of confirmed theory of the normal feedback oscillator to explain the operation of the blocking oscillator while, at the same time, drawing from the recorded experimental facts portions of the explanation not to be correctly inferred from the regular feedback oscillator theory.

THE NORMAL FEEDBACK OSCILLATOR

A vacuum tube is said to be in an oscillatory state when it is converting D-C power in the plate circuit into A-C power available from the output circuit, with no external A-C input of any kind into the circuit.

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The conditions necessary for oscillation are well known. These conditions are: a) feedback of sufficient magnitude from the output to the input to overcome circuit losses, and b) feedback of such phase that it will aid, or be in phase with, the voltage in the grid or input circuit.

In order that these conditions be met three separate functions must be performed by the oscillator tube and its associated circuit.(10) These functions are: a) amplifying, b) amplitude limiting, and c) filtering. These functions are necessary and sufficient for the operation of a feedback oscillator. They are illustrated in the "closed" block diagram of Figure I. The amplifier portion must overcome the losses of the system; that is, output must exceed input. The filter includes any and all devices used to insure that the output has a definite frequency. It includes RC networks as well as high Q tuned circuits. The limiter determines the level at which sustained oscillations are generated. This function, as well as that of amplifying, is often accomplished by the vacuum tube.

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Thus the question of whether or not it will oscillate involves the efficiency of the circuit--the amount of feedback required to overcome losses--the tube employed and the operating potentials on the tube. Grid bias voltage has a definite effect upon the ease of starting oscillations. If the initial impulse is so small that it cannot cause a variation in the plate circuit because the grid bias is too high, oscillations will not start automatically.

For comparison purposes later on in the paper the operation of the feedback oscillator shown in Figure II will be explained in some detail. This particular feedback oscillator is choosen because of the similarity of the circuit to that of the blocking oscillator. (Refer to Figure II_A).

When the cathode is energized electrons flow to the plate.(2) This means that a rising current is initiated in L_1, because plate current increases as the cathode heats up. Since L_2 is inductively coupled to L_1 a voltage is induced in L_2.

There is no fixed bias on the grid and at the outset its potential is zero. Therefore, a small voltage on the grid will cause an immediate change of plate current. If, for instance, the voltage induced in L_2 is positive, this positive voltage appearing at the grid will cause a further increase in the plate current. This increase in current tube employed and the operating potentials on the tube. Grid bias voltage has a definite effect upon the ease of starting oscillations. If the initial impulse is so small that it cannot cause a variation in the plate circuit because the grid bias is too high, oscillations will not start automatically.

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This completes the feedback action of the transformer but no reference has been made to the tank circuit action of L_2C_2 in the grid circuit.

When a voltage is induced in L_2 the capacitor C_2 is charged up. When it has reached its capacity it will discharge through L_2 setting up an oscillatory current. Since C_2 charges and discharges in first one direction hastens the expansion of the field about L_g inducing a still greater positive voltage in L_g making the grid more positive, thereby contributing to increase the plate current still further. This cycle process continues until some limiting value of plate current is reached. When the plate current can no longer increase as rapidly there will be less voltage induced in L_g. The voltage on the grid thus reaches a maximum and begins to decrease. With the grid less positive than before the plate current begins to decrease. The magnetic field about L_g begins to collapse and a voltage of opposite polarity is induced in L_g. This decreases the grid voltage which, in turn, decreases the plate current even more. This cyclic process continues until the plate current decrease is negligibly small. At this point no voltage is induced in L_g and the grid returns to zero potential; the cycle then repeats.

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While the two separate actions detailed above are taking place, still a third action is going on simultaneously. This is the regulating action of the R_gC_g combination in the grid circuit. A negative bias is produced on the grid by this combination in the following manner. With the initial excitation signal at such a frequency that C_g offers little impedance to it, the signal bypasses R_g and is placed upon the grid. During positive signal alterations the grid draws current. This D-C flows in the external circuit from cathode, through L_g and R_g to the grid. By the voltage drop through R_g, the grid is made negative with respect to the cathode. This voltage places a charge on the condenser C_g. During the negative portion of the signal voltage the capacitor C_g attempts to discharge through R_g. The rate at which discharge takes place depends upon the values of R_g and C_g. The greater the product R_gC_g the longer it will take for the discharge. This product is called the time constant. The time constant and then the other through L_g the frequency of the oscillatory currents depends upon the values of L_g and C_g. If, however, the energy were not replenished once each cycle by the feedback from L_1 to L_g the oscillations would die out.

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An increase or decrease in plate current is reflected at once in a change in the excitation voltage induced in L_g. This is followed by an increase or decrease in the grid bias which opposes further changes of the plate current in the same direction. Thus the grid bias, which is determined by the values of R_g and C_g, exerts a regulating action upon the plate current.

In this feedback oscillator the tube acts as an amplifier and, in conjunction with the R_gC_g circuit, as a limiter. The tuned circuit in the grid circuit acts as the filter. Also, the magnitude of the feedback is regulated by the R_gC_g combination subject to the fixed coupling of L_1 and L_g. The phase of the feedback is properly determined by the connection of the grid to the appropriate end of L_g.

With regard to the regulating action of the R_gC_g combination, let it be supposed that C_g is too large. It will then take considerable time for its charge to leak off through R_g. The grid will be insensitive to a sudden change in the average plate current. The tube, having a large negative bias, will cease conducting. Oscillations will stop. They will not start is usually made large compared to the period of one cycle so that the charge on the condenser C_g does not fall off appreciably during the time of one cycle.

An increase or decrease in plate current is reflected at once in a change in the oscillator voltage induced in L_g. This is followed by an increase or decrease in the grid bias which opposes further changes of the plate current in the same direction. Thus the grid bias, which is set up by the values of R_g and C_g, exerts a regulating action upon the plate current.

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The criterion for self modulation of an oscillator has been set forth by Edson[10] employing a Nyquist diagram[4] wherein a plot of the vector ratio of output to input modulation is made. The Nyquist criterion is thus modified by Edson so as to indicate whether a particular unstable system (an oscillator) has or lacks stability as to self modulation. As usual in the Nyquist diagram, if the locus of the end point of this vector encloses the point $1 + j0$ instability is indicated. Instability in this case means that the oscillations are unstable and that the system will again until the grid is restored to a value of bias that will permit some flow of plate current. That is, oscillations will not again take place until the capacitor C_g has had time to discharge through R_g to a sufficient point where the grid bias is low enough to permit oscillations. So, the rate at which oscillations are interrupted depends upon the product R_gC_g. This action is the equivalent of modulation of the generated R.F. voltage, and is often referred to as self modulation. It is also often referred to as intermittent operation; an oscillator operating in such a fashion being known as an intermittent or blocking oscillator.

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To obtain a locus such as is shown in Figure III, the oscillator circuit is opened and connections are made as shown in Figure IV. The test generator supplies an amplitude modulated wave of low frequency and small amplitude to the oscillator. This modulation is transmitted through the amplifier, the filter and the limiter to the test detector. The input may be taken from the test generator and the output from the test detector. These are both vector quantities and their ratios will be a vector. It is this vector that is plotted to give a locus such as is shown in Figure III.

So if one wishes to know whether a given oscillator is subject to intermittent operation, it may be determined. Furthermore, if there exists a blocking (intermittent) oscillator one may use this scheme to determine the reliability of the operation because if the plot encircles the 1 + jo point by a wide margin then operation as a blocking oscillator is assured while, if it encircles this point closely, marginal operation is indicated.

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It should be noted that this scheme is predicated upon having a blocking oscillator physically available for test. It does not, therefore, give specific design information to one who seeks to design a blocking oscillator. That is, it is a test measure rather than a design measure.

THE BLOCKING OSCILLATOR

An oscillator which is operating intermittently is called a blocking oscillator because during the time when no oscillations are taking place the flow of plate current is "blocked" by the high negative grid bias.

This phenomenon should not be confused with an entirely different phenomenon which is also referred to as "blocking".(15) In the latter phenomenon the grid is driven extremely positive, and "blocking" takes place due to grid current reversal caused by thermal or secondary emission from the grid. This type of blocking is very injurious to the tube and may destroy it.

The blocking oscillator has been defined in various ways. Some authors indicate that it is a distinctly different device;(14) others define it as a relaxation oscillator;(18) others as an impulse generator;(20)

and still others define it as merely an oscillator with intermittent operation.(12)(13)(15)

The last definition appears to be more acceptable because it refers to the theory of operation of the device and not to its use. This definition is here taken as being correct. It has been given previously in the first page of this paper.

After defining the blocking oscillator in this way, it may be classified as to its use or operation in a circuit. For instance, a driven blocking oscillator may be employed in a circuit as an impulse generator. Furthermore, this definition does not exclude either of the two basic types of blocking oscillators: 1) the multiple swing (self-pulsed) blocking oscillator and, 2) the single swing blocking oscillator.

THE MULTIPLE SWING (SELF-PULSED) BLOCKING OSCILLATOR

Definition

The multiple swing blocking oscillator is not usually the device one has in mind when speaking of a blocking oscillator. It does fall within the definition and the explanation of its operation, which has already been alluded to, logically follows from that of the normal feedback oscillator.

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It is called the multiple swing blocking oscillator because the plate current must swing through several high frequency oscillations before the bias on the grid goes far enough negative to cut the tube off. It is also referred to as the self-pulsing blocking oscillator because its output is a series of pulses of high frequency energy, the pulse recurrence rate being determined by self-contained components of the circuit, R_g and C_g.

In this oscillator intermittent operation, which was undersirable in the normal feedback oscillator, is purposely obtained by making the values of R_g and C_g so large that the oscillator cannot oscillate continuously. By choosing the values of R_g and C_g the pulses of high frequency energy may be made to occur at a desired rate. Thus a "fault" of the normal feedback oscillator is converted into a desirable function.

OPERATION

For the explanation of the operation of this oscillator, reference is again made to Figure II. In this figure, regard the values of R_g and C_g as having been changed from the previous values to some values corresponding to a desired pulse recurrence frequency. The operation of the feedback transformer and that of

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When oscillations begin in the plate circuit, through feedback to the grid circuit, a positive voltage is placed on the grid. The grid draws current. A D-C voltage drop is produced across R_g and C_g is charged to this voltage. Since C_g receives more charge from each cycle of feedback voltage than it loses through R_g during the cycle, a negative charge begins to accumulate on the grid and the intensity of oscillation decreases. C_g receives more charge than can leak away during each cycle because the R_gC_g time constant is so high that C_g cannot discharge rapidly; the grid therefore stays at a large negative bias even though the plate current, and hence the feedback, is decreasing.

Thus the regulating action of the grid-leak condenser combination does not operate rapidly enough and the oscillations die out. Since the high negative bias is retained on the grid until such time as C_g discharges through R_g, oscillations will not start again until C_g has discharged sufficiently to allow the grid bias the L C combination in the grid circuit is the same as detailed above for the normal feedback oscillator. The operation of the R_gC_g combination is different, however. The explanations of this action are given in the following pages.

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The action of the R_gC_g combination in producing the delayed regulating action of the grid is illustrated in Figure V.[12] Figure VI illustrates in detail the build-up of the negative voltage on the grid through the charging action of the high frequency oscillation feed-back from the plate to the grid circuit by the trans-former L_1 L_2.

The regulating action in this oscillator may be explained in another way. This is with reference to the conductance of the plate circuit. To follow this explanation, reference should be made to Figures VII and VIII.[18] In the discussion to follow, g is the con-ductance that a generator would see if coupled to points A and B, Figure VII. In Figure VIII the solid curve of conductance vs amplitude represents an os-cillator in which the grid bias is dependent upon the amplitude of the oscillations. Point P represents a point of oscillation since at this point the "negative" resistance due to feedback into the grid circuit exact-ly equals the "positive" resistance. The conductance is then zero. Furthermore, point P is a stable op-erating point on the solid curve because as the am-plitude increases the conductance changes, due to a to become low enough for the multiplying action of the tube to start the oscillations.

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Since the multiple swing blocking oscillator is not a stable oscillator---ie. stable in the sense of continuous high frequency oscillations---it does not follow the solid curve; instead it follows such a curve as the dotted one. With reference to this curve point P is no longer a point of stable equilibrium. Consider for example that there is a sudden decrease in the amplitude of oscillations. There is now very little change in grid bias, due to the delayed regulating action of R_g and C_g, so that this decrease in amplitude of oscillations continues. It continues until point X is reached, at which time conduction in the tube ceases. At this point, since there is no flow of plate current, $g = 1/R_L$. As previously stated, when C_g has discharged sufficiently the grid again allows the tube to conduct. The conductance begins to decrease with increased feedback and as soon as it again reaches point P oscillations are initiated and the cycle repeats.

change in grid bias as explained for the normal feed-back oscillator above, and the amplitude of oscillations is decreased by this action thus returning to point P. A similar explanation holds for reduced amplitude. Stability about point P is indicated by the two arrows drawn along the solid curve pointing toward P.

Since the multiple swing blocking oscillator is not a stable oscillator--ie. stable in the sense of continuous high frequency oscillations--it does not follow the solid curve; instead it follows such a curve as the dotted one. With reference to this curve point P is no longer a point of stable equilibrium. Consider for example that there is a sudden decrease in the amplitude of oscillations. There is now very little change in grid bias, due to the delayed regulating action of R_g and C_g, so that this decrease in amplitude of oscillations continues. It continues until point Z is reached, at which time conduction in the tube ceases. At this point, since there is no flow of plate current, $g = 1/R_p$. As previously stated, when C_g has discharged sufficiently the grid again allows the tube to conduct. The conductance begins to increase with increased feedback and as soon as it again reaches point P oscillations are initiated and the cycle is repeated.

It might appear at first that these two explanations of the regulating action of R_gC_g contradict each other. Such is not the case because they both depend upon finite changes in the amplitude of oscillations and in the grid bias. How then, one might ask, can the increase in amplitude of high frequency oscillations shown in Figure VI between points J and K be reconciled with the action set forth by Figure VIII? This can be reconciled as follows: point J in Figure VI corresponds to point F in Figure VIII as oscillations are initiated. The conductance is going negative, hence oscillations may increase slightly. By this very increase in amplitude of oscillations the grid acquires a greater negative bias which tends to limit the increase in amplitude momentarily and to decrease the amplitude thereafter. Points K on Figure VI and Y on Figure VIII correspond to this point of maximum amplitude. From this maximum value the transition is made quickly back through point I on Figure VIII, which corresponds to point I on Figure VI, and the oscillations quickly die out.

Some objection may be made to the assumption that finite changes take place in the amplitude of oscillations and grid bias. Such objections may be valid for

It might appear at first that these two explanations of the regulating action of R_gC_g contradict each other. Such is not the case because they both depend upon finite changes in the amplitude of oscillations and in the grid bias. How then, one might ask, can the increase in amplitude of high frequency oscillations shown in Figure VI between points A and F be reconciled with the action set forth by Figure VIII? This can be reconciled as follows: point A in Figure VI corresponds to point P in Figure VIII as oscillations are initiated. The conductance is going negative, hence oscillations may increase slightly. By this very increase in amplitude of oscillations the grid acquires a greater negative bias which tends to limit the increase in amplitude momentarily and to decrease the amplitude thereafter. Points F on Figure VI and T on Figure VIII correspond to this point of maximum amplitude. From this maximum value the transition is made a fairly [illegible] through point [illegible] on Figure VIII, which corresponds to point [illegible] on Figure VI, and the oscillations quickly die out.

Some objection may be made to the supposition that finite changes take place in the amplitude of oscillations and grid bias. Such objections may be valid for it is probable that it is not necessary to assume a finite change in amplitude or grid bias. Neverthe-less, a decrease in amplitude decreases the grid bias (refer to Figure VI to the right of point L). A dif-ferential change in amplitude is not, however, accom-panied by a sudden finite rate of decrease of grid bias. These objections could doubtless be answered in the exact mathematical analysis very easily by the passage to the limit of $\frac{\Delta E}{\Delta t}$ or $\frac{\Delta e_g}{\Delta t}$,

eg.

$$\lim_{\Delta t \to 0} \frac{\Delta E}{\Delta t} = \frac{dE}{dt}.$$

In the qualitative discussion it is impossible to per-form such an operation, so the objections must stand. It is not uncommon to find in the literature explana-tions of phenomena given qualitatively by finite changes while mathematically these finite quantities may be replaced with the more exact differential quan-tity. This limitation on the qualitative analysis need not limit the understanding of the actual occur-rences as set forth above.

The nearest approach to an exact mathematical analysis of the above operation so far produced is that by van der Pol.(2) His analysis was not made for the particular circuit shown in Figure II and is not it is probable that it is not necessary to assume a finite change in amplitude or grid bias. Nevertheless, a decrease in amplitude decreases the grid bias (refer to Figure VI at the right of point A). A differential change in amplitude is not, however, accompanied by a sudden finite rate of decrease of grid bias. These objections could doubtless be answered in the exact mathematical analysis very easily by the passage to the limit of $\frac{\Delta E}{\Delta t}$ or $\frac{\Delta e_g}{\Delta t}$,

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The present account is an exact qualitative analysis of the above operation as far evolved in part by van der Pol.(8) The analysis was not made for the special circuit shown in Figure II and is not directly applicable to Figure II without considerable modification. He does go into the matter of amplitude limiting, "negative" resistance by feedback, and variation of the waveform of the output with changes in the R_gC_g time constant. He writes an equation of the Ricatti type and solves it by a partially analytical, partially graphical method. The graphical portion is known as the method of isoclines. From this work, since it is shown that the maximum steady state amplitude is always the same regardless of the shape of the output waveform, it can reasonably be inferred that the maximum amplitude of the multiple swing blocking oscillator would remain steady regardless of the length of the pulse or the time between pulses. Also from this work it may be possible for someone to find a point of departure for the analytical analysis of the operation of the multiple swing blocking oscillator.

DESIGN

The design of such an oscillator may be carried out in a manner analogous to that for the normal feedback oscillator. This design, it will be recalled, follows that for a class C power amplifier.[(7)(15)] Although an exact set of circuit parameters cannot be obtained an approximation as close as desired may be obtained.

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DESIGN

The design of such an oscillator may be carried out in a manner analogous to that for a normal feedback oscillator. This design, it will be recalled, follows that for a class C power amplifier.[25][7] Although an exact set of circuit parameters cannot be obtained an approximation as close as desired can be obtained.

(13)
The contour chart showing conditions for an oscillator, illustrated in Figure IX, yields part of the necessary design information. From it, one may determine whether blocking (or self-pulsing) is apt to take place. If the excitation line and the R_{Lo} line do not intersect continuous oscillation is impossible. The two lines may fail to intersect because of several reasons, one of them being because the grid bias becomes too great. When the grid bias recedes toward zero the two lines intersect and oscillations again take place until the grid bias separates the lines, thus repeating the cycle of pulsing. As can be seen from studying Figure IX, this intermittent operation may be accentuated by decreasing the excitation ratio or by decreasing R_{Lo}. In this figure,

$$R_{Lo} = \frac{\hat{E}_p^{\,2}}{2(P_L - P_d)}$$

where $\hat{E}_p$ is the magnitude of the plate voltage

P_L is the power delivered to the load

P_d is the driving power supplied to grid

R_{Lo} is the equivalent resistance of the load circuit

Having designed the oscillator for intermittent operation, one may then build the oscillator according

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Having designed the oscillator for intermittent operation, one may then modify the oscillator according to this design and check its operation by Edson's method, previously referred to in this paper.

APPLICATIONS

The multiple swing blocking oscillator has seen considerable use in electronic equipment employed by the Armed Services of this country. It has most often been used in radar and IFF equipment as a self-pulsed transmitter. In this capacity it functions as a high frequency oscillator, a modulator and PRF generator combined giving forth periodic bursts of R.F. energy.

Figure X is a diagram of the multiple swing blocking oscillator used as a PRF generator.(19) The circuit oscillates at about 80 megacycles per second and the PRF (Pulse Recurrence Frequency) is variable from about 50 cycles per second to 5,000 cycles per second.

Other applications for this oscillator are its use as a demodulator in superregenerative receivers and as an audio frequency modulator in certain radiosonde equipment.

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The use of the multiple swing blocking oscillator, although considerable, is not nearly as extensive as is the use of the single swing blocking oscillator.

THE SINGLE SWING BLOCKING OSCILLATOR

GENERAL

The uses of the single swing blocking oscillator will be deferred until later on in the paper after its design and operation have been considered. The knowledge that this oscillator has many and varied uses will explain to the reader why it has been the subject of so much experimental study. It will explain, too, the reason for considering the single swing blocking oscillator in detail. Yet, while these things are explained, it may cause him to ask why an analytical analysis of the operation of this important device has never been made. The question as to why such an analysis has not been made will remain unanswered but the answer will surely be indicated in part when the reader views the complexity of the operations which must be analyzed. These operations are considered qualitatively, with mathematics being introduced only after simplifying assumptions have been made.

DEFINITION

The single swing blocking oscillator is so called because the plate current swings through only a single positive half cycle before the grid bias goes so far negative that the tube is cut off.

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[illegible]

The single swing blocking oscillator [illegible] [illegible]

[illegible]

[illegible]

QUALITATIVE RESUMÉ OF OPERATION

By referring to Figure XI and the waveforms shown in Figure XII the following brief account of the operation of the free running blocking oscillator may be followed. Consider the grid bias to be at the cutoff value and going less negative due to discharge of the capacitor C_g. Plate current is initiated and a magnetic field builds up about L_1 inducing a voltage in L_g. This voltage is impressed upon the grid through C_g and the grid thereby rapidly becomes more positive. When the grid goes positive with respect to the cathode, grid current flows and a charge is accumulated on the capacitor C_g with the negative polarity connected to the grid. After a time the plate current reaches saturation; the magnetic field about L_1 ceases to increase and no voltage is induced in L_g. With no voltage applied to it the grid is less positive than its previous value and it therefore decreases the plate current. This decreasing current through L_1 changes the polarity of the voltage induced in the grid end of L_g; this voltage now starts swinging negative. With this "negative-going" voltage applied to the grid the plate current is sharply reduced. In turn, the voltage induced in L_g by the current change through L_1 is sharply reduced. This cumulative action continues until the

QUALITATIVE THEORY OF OPERATION

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From this brief resumé of the operation one is inclined to regard the present circuit and its operation as an extension of the multiple swing blocking oscillator where the tuned circuit damping is gradually increased permitting fewer and fewer radio-frequency cycles to be executed during each pulse. Actually as will be seen later, the extension has been pushed so far that the phenomena have taken on a somewhat different character. Furthermore, the waveform of the output is quite different from that of the multiple swing oscillator because only one "frequency" is involved, that being the pulse recurrence frequency.

In view of these changes it is appropriate to inquire into the causes which produced them. Referring back to the above resumé of the operation it is found that: a) the circuit acts as an oscillator even though the energy output consists of pulses, b) it has feedback from I_1 to I_g just as the multiple grid is driven well beyond cutoff. Plate current ceases to flow and will not again flow until the bias maintained on the grid by C_g is reduced sufficiently, by the discharge of C_g through R_g, to allow the tube to conduct.

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In view of these changes it is appropriate to inquire into the causes which produced them. Referring back to the above resumé of the operation it is found that: a) the circuit acts as an oscillator even though the energy output consists of pulses, b) it has feedback from I_p to I_g just as the multiple swing blocking oscillator does, c) it employs a grid leak and condenser combination for grid bias, d) the grid is periodically driven considerably positive and then far beyond cutoff in a manner similar to that for the multiple swing blocking oscillator except that the grid bias changes more per pulse of plate current in this case. With these similarities existing, one is able to gain considerable insight into the operation of the single swing blocking oscillator. But, to explain the change in operation in going from the multiple swing blocking oscillator to the single swing blocking oscillator and why the output waveforms differ, other facts are required.

In proceeding from the normal feedback oscillator to the multiple swing blocking oscillator a change in the values of R_g and C_g took place and this change of values accounts entirely for the change in operation in going from the normal oscillator to the multiple swing blocking oscillator. In the present transition, however, the change in operation is not due entirely to changes in the values of R_g and C_g. Rather, it is more due to the increased inductance of the feedback transformer, its distributed capacitance, and the close coupling of the plate to the grid circuit swing blocking oscillator does, c) it employs a grid leak and condenser combination for grid bias, d) the grid is periodically driven considerably positive and then far beyond cutoff in a manner similar to that for the multiple swing blocking oscillator except that the grid bias changes once per pulse of plate current in this case. With these similarities existing, one is able to gain considerable insight into the operation of the single swing blocking oscillator. But, to explain the change in operation in going from the multiple swing blocking oscillator to the single swing blocking oscillator and why the output waveforms differ, other facts are required.

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through this transformer. It should now be noted that the transformer in Figure XI is an iron core transformer while that of Figure II is an air core transformer.

Although it is difficult to prove analytically that changing the values of R_g and C_g and changing the feedback transformer from an air core to an iron core accounts for the changed operation, experiment has substantiated this fact. It is to these experimentally recorded facts that one must turn if "proof" is required. From these recorded data one may, however, glean considerably more information than just this "proof". He is able to determine the effects of all parts of the circuit upon the shape of the output waveform and is able, therefore, to pick more intelligently the type of tube, the transformer, and the values of R_g and C_g to fulfill specific design requirements. In addition, the final gaps in the knowledge of the operation of the single swing blocking oscillator are filled.

DETAILED THEORETICAL (QUALITATIVE) ANALYSIS OF OPERATION

Before resorting to information and theory based upon experiment another theoretical explanation of the operation of the single swing blocking oscillator will be given. (18) In this explanation more details are brought out and, in particular, the feedback transformer, with through this transformer. It should now be noted that the transformer in Figure XI is an iron core transformer while that of Figure II is an air core transformer.

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[illegible]

Before proceeding to information and theory based upon experiment and/or theoretical explanation of the operation of the single swing blocking oscillator will be given. [illegible] its iron core, and the R_gC_g combination are considered in some detail. Certain assumptions are involved. The validity of these assumptions will be discussed following the explanation.

Refer to Figure II_A and make the following assumptions: a) that the voltage on the grid condenser remains essentially constant during that portion of the cycle of operation represented between points A and D on Figure XIII, b) that the transformer L_1L_2 is an ideal transformer with no leakage inductance or capacitance, and c) that the effects of interelectrode capacity are negligible.

Consider that the condenser voltage has maintained the tube cut off and decreases so that current starts to flow. A voltage, i_pR_L, then appears across L_1 and in turn a voltage, $\rho i_p R_L$, is added to the grid circuit in a direction tending to increase the plate current flow. The condenser voltage is,

$$1)\quad e_{cg} = \left[R_g + \frac{\rho^2 R_L r_p}{R_L + r_p} \right] i + \rho R_L i_p$$

where i_p is the plate current

i is the current in the grid loop containing L_2, C_g and R_g

ρ is the transformer ratio

r_p is the plate resistance

its iron core, and the R_gC_g combination are considered in some detail. Certain assumptions are involved. The validity of these assumptions will be discussed following the explanation.

Refer to Figure 11A and make the following assumptions: a) that the voltage on the grid condenser remains essentially constant during that portion of the cycle of operation represented between points A and D on Figure XIII, b) that the transformer L_pL_g is an ideal transformer with no leakage inductance or capacitance, and c) that the effects of interelectrode capacity are negligible.

Consider that the condenser voltage has maintained the tube cut off and decreases so that current starts to flow. A voltage, $L_p\dot{i}_p$, then appears across L_p and in turn a voltage, $\rho i_p R_L$, is added to the grid circuit in a direction tending to increase the plate current flow. The condenser voltage is,

$$11)\quad e_{cg} = \left[R_g + \frac{\rho^2 R_L r_p}{R_L + r_p} \right] i + \rho R_L i_p$$

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i is the current in the grid loop containing C_g and R_g

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R_L , R_g , C_g and C_g are as shown in Figure II_A. Approximately,

2) $e_{cg} = R_g i + \rho R_L i_p$

3) $e_{cg} = -e_g + \rho R_L i_p$

A point is eventually reached where a change in grid voltage is more than compensated for by a change in the voltage across I_g. This can be seen by differentiating equation 3).

4) $$\frac{de_{cg}}{dt} = -\frac{de_g}{dt} + \rho g_m R_p \frac{de_g}{dt}$$

where

5) $$\frac{1}{R_p} = \frac{1}{R_L} + \frac{1}{r_p} + \frac{\rho^2}{R_g}$$

Also,

6) $$-i = \frac{e_g}{R_g} = C_g \frac{de_{cg}}{dt}$$

or, from 6)

7) $$\frac{de_{cg}}{dt} = \frac{e_g}{C_g R_g}$$

Equating 7) and 4)

8) $$\frac{e_g}{C_g R_g} = -\frac{de_g}{dt} + \rho g_m R_p \frac{de_g}{dt}$$

R_L, R_g, C_g and C_g are as shown in Figure 17a. Approximately,

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8) $$\frac{e_g}{C_g R_g} = -\frac{de_g}{dt} + \rho g_m R_p \frac{de_{cg}}{dt}$$

Solving for $\frac{de_g}{dt}$,

9) $$\frac{de_g}{dt} = \frac{-e_g}{R_g C_g (1 - \rho g_m R_p)}$$

Equation 9) shows that the change of grid voltage during the time when no plate current flows, the condition postulated at the beginning of this paragraph, is in a direction opposite to that of the grid voltage itself. In the absence of plate current,

10) $$\rho g_m = 0$$

and then

11) $$\frac{de_g}{dt} = \frac{-e_g}{R_g C_g}$$

Thus, if the voltage e_g is negative, the rate of change, $\frac{de_g}{dt}$, is positive and the voltage on the grid is thus made less negative. As the grid voltage goes less negative and plate current starts to flow, the term $\rho g_m R_p$ is no longer zero but takes on a finite value and partially cancels the other term. From this theory $\frac{de_g}{dt}$ tends to become infinite as the two terms in the denominator of 9) approach equality. Actually $\frac{de_g}{dt}$ never approaches infinity because of the interelectrode capacitance. It does, however, become very large and explains why the grid voltage swings

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$$12)\quad E_{BB} = i_p R_L - \frac{i_g R_L}{\rho} + e_p$$

In this equation e_p is the plate voltage at which i_g and i_p flow when

$$13)\quad e_g = e_{cg} - \frac{E_{BB} - e_p}{\rho}$$

With the grid rapidly reaching the highly positive value at point D, grid voltage drops sharply to zero, point F. The tube ceases to conduct and the sharp decrease in the plate current rapidly drives the plate voltage upward and, by feedback from L_1 to L_g, drives the grid voltage downward well past cutoff. The operating point moves quickly back to point A along the line F-A with a slope $-\frac{1}{\rho}$. The condenser C_g slowly loses its charge again through R_g, the grid becomes more positive and the cycle repeats.

As for the validity of the assumptions made above, it has been seen that the interelectrode capacity cannot be neglected entirely for then an infinity results in equation 9). This assumption is therefore valid over only a limited portion of the cycle. The condition that the voltage e_{cg} remains substantially constant over that portion of the cycle between points A and D may be closely approximated if C_g is very much greater than the interelectrode capacitance and if L_1 L_g approaches an ideal transformer. C_g is normally very large compared to the interelectrode capacity but the ideal transformer can only be approximated. Obviously e_{cg} cannot actually be constant for, if it were equation 7) would go to zero and the cycle would not repeat.

Even in this oversimplified mathematical treatment difficulties appear. In the exact mathematical analysis further difficulties would be encountered. Certain difficulties having to do with non linearities involved in relaxation oscillators are covered in Minorsky's book.(22) Many of the difficulties pointed out by Minorsky evidently apply directly to the single swing blocking oscillator although this oscillator is not specifically analyzed by Minorsky. No general rules of procedure are set forth by Minorsky on how the exact analysis of the single swing blocking oscillator may be carried out. It appears that writing an equation of the van der Pol type and solving it by the isocline method has the most promise; at any rate, it would be a starting point. Fortunately, however, an exact mathematical analysis is not required because of the experimental work that has been done and the theory developed to explain this experimental work.

TYPES OF SINGLE SWING BLOCKING OSCILLATORS

It will be noted in the above description of the operation that the action taking place repeated itself. Since conduction of the tube was automatically cut off and on by its associated circuit, without the application

Even in this oversimplified mathematical treatment difficulties appear. In the exact mathematical analysis further difficulties would be encountered. Certain difficulties having to do with non linearities involved in relaxation oscillators are covered in Minorsky's book.(22) Many of the difficulties pointed out by Minorsky evidently apply directly to the single swing blocking oscillator although this oscillator is not specifically analyzed by Minorsky. No general rules of procedure are set forth by Minorsky on how the exact analysis of the single swing blocking oscillator may be carried out. It appears that writing an equation of the van der Pol type and solving it by the isocline method has the most promise; at any rate, it would be a starting point. Fortunately, however, an exact mathematical analysis is not required because of the experimental work that has been done and the theory developed to explain this experimental work.

[illegible] OSCILLATORS

It will be noted in the above description of the operation that the action taking place repeated itself. Time duration of the [illegible] was automatically cut off and only by its associated [illegible], with the [illegible] of an external trigger pulse, this single swing blocking oscillator is called an astable blocking oscillator.(19) It is more commonly referred to as the free running blocking oscillator. Such an oscillator may have a small voltage applied to the grid of the tube so that the tube is made to conduct an instant before it would normally conduct; the device is then called a synchronized astable blocking oscillator. If the action in such a circuit as Figure XI does not repeat itself because the grid is maintained at a bias beyond cut off, by fixed bias, an external trigger pulse must be applied to drive the tube into conduction; it is then called a monostable blocking oscillator. It is more commonly called a driven blocking oscillator. Thus far, discussion has been centered around the free running (astable) blocking oscillator and this will continue because it is the most general of the three types referred to above.

SEMI-MATHEMATICAL THEORY OF OPERATION BASED UPON EXPERIMENT

Turning now to the theory of operation based upon observation of the output waveform, the action of the free running blocking oscillator is broken down into three separate but contiguous actions.(16) This analysis is qualitative and semi-mathematical in nature and of an external trigger pulse, this single swing blocking oscillator is called an astable blocking oscillator.(15) It is more commonly referred to as the free running blocking oscillator. Such an oscillator may have a small voltage applied to the grid of the tube so that the tube is made to conduct an instant before it would normally conduct; the device is then called a synchronized astable blocking oscillator. If the action in such a circuit as Figure XI does not repeat itself because the grid is maintained at a bias beyond cut off, by fixed bias, an external trigger pulse must be applied to drive the tube into conduction; it is then called a monostable blocking oscillator. It is more commonly called a driven blocking oscillator. Thus far, discussion has been centered around the free running (astable) blocking oscillator and this will continue because it is the most general of the three types referred to above.

III-[illegible] THEORY

Turning now to the theory of operation based upon observation of the output waveforms, the action of the free running blocking oscillator is broken down into three separate but continuous actions.(16) This analysis is qualitative and semi-mathematical in nature and involves the action taking place during: a) rise of the pulse, b) the top of the pulse, c) fall of the pulse or tail of the pulse. Certain assumptions and approximations are involved but, from the mathematics here presented, one is able to obtain quantitative information on circuit parameters not available in other analyses.

Consider the astable blocking oscillator of Figure XI. Note that the voltage ratio between plate and grid is -1 since the dot end of L_g is connected to the grid while the dot end of L_1 is connected to the power source; the dot refers, as usual, to the end of L_g that is positive when the dot end of L_1 is positive.

In order that linear differential equations may be written and their solution obtained by the Laplace transform operational method, the plate resistance, r_p, and the amplification factor, μ, of the tube will be considered constant during the part of the pulse under immediate consideration.

<u>The Rise of the Pulse--Case I.</u> In the initial calculations the following simplifying assumptions are made: a) that r_p is zero, b) that the effect of leakage inductance is negligible compared to R, c) that C is zero, and d) that the plate-to-grid capacitance C_{gp} of the

involves the coupled taking place during, a) rise of the pulse, b) the top of the pulse, c) fall of the pulse or tail of the pulse. Certain assumptions and approximations are involved but, from the schematics here presented, one is able to obtain quantitative information on circuit parameters not available in other techniques.

Consider the unstable blocking oscillator of Figure 1. Note that the voltage mutual between plate and grid is -1 since the dot end of L_g is connected to the grid while the dot end of L_p is connected to the power source; the dot refers, as usual, to the end of L_g that is positive when the dot end of L_p is positive.

In order that linear differential equations may be written and their solution [illegible] the [illegible] transfer operational [illegible] resistance, R_p, and the amplification factor, μ, [illegible] will be considered [illegible] of the [illegible] two major [illegible].

The Rise of the Leading Edge. [illegible]

[illegible] R_p is zero, [illegible] C is zero, [illegible] C_{gp} of the tube is negligible. With these assumptions the equivalent circuit of Figure XI is given in Figure XIV. In this figure C_D is the effective distributed capacitance of the transformer and E_c is the bias voltage which is given by

14) $$E_c = E_{co} + \epsilon$$

where E_{co} is the cutoff bias and ϵ is a vanishingly small positive voltage, sufficient in magnitude, however, to initiate regeneration. Now let

15) $$e_{g_1} = |e_g - E_{co}|$$

and the equivalent circuit of Figure XIV may be further simplified to that of Figure XV. Applying Kirchhoff's voltage-law to Figure XV, write

16) $$Ri + \frac{1}{C_D}\int i\,dt = \mu e_{g_1} + \epsilon$$

(21)

Using the standard notation of Gardner and Barnes where

17) $$\mathcal{L}\left\{i(t)\right\} \triangleq I(s) \quad \text{AND} \quad \mathcal{L}\left\{e_{g_1}(t)\right\} \triangleq E_{g_1}(s)$$

and noting that the initial voltage on C_D is zero, the Laplace transform of 16) is

18) $$\left[R + \frac{1}{C_D S}\right] I(s) = \frac{\mu E_{g_1}(s)}{S} + \frac{\epsilon}{S}$$

tate is negligible. With these assumptions the equivalent circuit of Figure II is given in Figure XIV. In this figure C_D is the effective distributed capacitance of the transformer and E_c is the bias voltage which is given by

14) $E_c = E_{co} + \epsilon$

where E_{co} is the cutoff bias and ϵ is a vanishingly small positive voltage, sufficient in magnitude, however, to initiate regeneration. Now let

15) $e_{g1} = |e_g - E_{co}|$

and the equivalent circuit of Figure XIV may be further simplified to that of Figure XV. Applying Kirchhoff's voltage-law to Figure XV, write

$$16) \quad Ri + \frac{1}{C_D}\int i\,dt = \mu e_{g1} + \epsilon$$

Using the standard notation of Gardner and Barnes where (21)

$$17) \quad \mathcal{L}\left\{i(t)\right\} \triangleq I(s) \text{ and } \mathcal{L}\left\{e_{g1}(t)\right\} \triangleq E_{g1}(s)$$

and noting that the initial value of i in C_D is zero, the Laplace transform of 16) is

$$18) \quad \left[R + \frac{1}{C_D s}\right] I(s) = \frac{\mu E_{g1}(s)}{s} + \frac{\epsilon}{s}$$

From the figure it is seen that

$$19) \quad e_{g_1}(t) = \frac{1}{C_D}\int i \, dt$$

so that

$$20) \quad E_{g_1}(s) = \frac{I(s)}{C_D S}$$

and

$$21) \quad \mu E_{g_1}(s) = \frac{\mu I(s)}{C_D S}$$

Substituting 21) into the right side of 18)

$$22) \quad \left[R + \frac{1}{C_D S}\right] I(s) = \frac{\mu I(s)}{C_D S} + \frac{\epsilon}{S}$$

Solving for $I(s)$

$$23) \quad I(s) = \frac{\epsilon/s}{\left[R + \frac{1}{C_D S}(1-\mu)\right]} = \frac{\epsilon}{S\left[R + \frac{1}{C_D S}(1-\mu)\right]}$$

Substituting $I(s)$ from 23) into 20)

$$24) \quad E_{g_1}(s) = \frac{1}{C_D S} \; \frac{\epsilon}{S\left[R + \frac{1}{C_D S}(1-\mu)\right]} = \frac{\epsilon}{C_D R S\left[S + \frac{1-\mu}{C_D R}\right]}$$

Since it has been assumed that the plate resistance is zero the change in plate voltage is given by:

From the figure it is seen that

$$19)\quad e_{g_1}(t) = \frac{1}{C_0}\int i\,dt$$

so that

$$20)\quad E_{g_1}(s) = \frac{I(s)}{C_0 s}$$

and

$$21)\quad \mu E_{g_1}(s) = \frac{\mu I(s)}{C_0 s}$$

Substituting (21) into the right side of (18)

$$22)\quad \left[R + \frac{1}{C_0 s}\right] I(s) = \frac{\mu I(s)}{C_0 s} + \frac{E}{s}$$

Solving for $I(s)$

$$23)\quad I(s) = \frac{E/s}{\left[R + \frac{1}{C_0 s}(1-\mu)\right]} = \frac{E}{s\left[R + \frac{1}{C_0 s}(1-\mu)\right]}$$

Substituting $I(s)$ from (23) into (20)

$$24)\quad E_{g_1}(s) = \frac{E}{C_0 s \; s\left[R + \frac{1}{C_0 s}(1-\mu)\right]} = \frac{E}{C_0 R s\left[s + \frac{1-\mu}{C_0 R}\right]}$$

25) $e_b(t) = -\mu\, e_{g_1}(t)$

or

26) $E_b(s) = -\mu\, E_{g_1}(s)$

so that

27) $$E_b(s) = \frac{-\mu\,\epsilon}{C_D R S\left[S + \frac{1-\mu}{C_D R}\right]}$$

Now taking the inverse Laplace transform of 27);

28) $$e_b(t) = -\mu\,\epsilon\,\frac{\left[\varepsilon^{\frac{\mu-1}{C_D R}t} - 1\right]}{\mu - 1}$$

In 28) if $\mu > 1$ the exponential term is positive and regeneration takes place until $|e_b| = E_{bb}$. It is here assumed that when the output voltage, $-e_b$ in this case, is equal to E_{bb}, μ becomes less than $+1$ and regeneration stops. Further, if it is assumed that during the rise $E_{bb} = \mu\,|E_{co}|$, μ must suddenly become less than $+1$ at the instant $e_{g_1} \geq |E_{co}|$. This necessitates a modification of the equivalent circuit the instant e_g passed through zero going positive because of the flow of grid current. This modification can be made quite readily because of the above assumptions that cause $|e_b| = E_{bb}$ at this instant and remain so as long as $e_g \geq 0$.

$$35)\quad e_t(t) = -\mu\, e_g(t)$$

or

$$36)\quad E_t(s) = -\mu E_g(s)$$

so that

$$37)\quad E_t(s) = \frac{-\mu E}{C_0 R s\left[s + \frac{1-\mu}{C_0 R}\right]}$$

Now taking the inverse laplace transform of 37):

$$38)\quad e_t(t) = -\mu E \frac{\left[\varepsilon^{\frac{\mu-1}{C_0 R}t} - 1\right]}{\mu - 1}$$

In 38) if $\mu > 1$ the exponential term is positive and regeneration takes place until $|e_t| = E_{tt}$. It is here assumed that when the output voltage, $-e_t$ in this case, is equal to E_{tt}, μ becomes less than $+1$ and regeneration stops. Finally, if it is assumed that before the value $E_{tt} = \mu|E_{co}|$, μ must suddenly become less than $+1$ at the instant $e_g \geq |E_{co}|$.

This demonstrates a realization of the equivalent circuit the instant e_g passed through zero going positive because of the flow of grid current. Then modification will be made [illegible] of the above assumption that never $|e_t| = E_{tt}$ at this instant and remain [illegible] as $e_g \geq 0$.

A more realistic assumption with regard to the average value of μ during the pulse rise would be:

29) $$\mu = \frac{E_{bb}}{\left[\,|E_{co}| + e_{g2}\right]}.$$

e_{g2} is a positive grid voltage at which μ begins to change abruptly from greater than $+1$ to a value less than $+1$. Even this more accurate assumption, as simple as it appears, introduces such complication that a linear solution in analytical form is difficult to obtain.

Case II---Condition A. To introduce the effects of L_L, the leakage inductance, consider the equivalent circuit shown in Figure XVI. For this figure, the Laplace transform of Kirchhoff's voltage equation is

30) $$\left[R + \frac{1}{C_D S} + L_L S\right] I(s) = \frac{\mu\, I(s)}{C_D\, S} + \frac{\epsilon}{S}$$

31) $$I(s) = \frac{\epsilon}{L_L\left[S^2 + \frac{R}{L_L} S + \frac{1}{L_L}\left(\frac{1-\mu}{C_D}\right)\right]}$$

Now using 30) again

32) $$E_{g_1}(s) = \frac{\epsilon}{L_L C_D S\left[S^2 + \frac{R_L}{L_L} S + \frac{1}{L_L}\left(\frac{1-\mu}{C_D}\right)\right]}$$

A more realistic assumption with regard to the average value of μ during the pulse time would be:

$$30)\quad \mu = \frac{E_{dd}}{\left[|E_{c0}| + e_{gx}\right]} .$$

e_{gx} is a positive grid voltage at which μ begins to change abruptly from greater than $+1$ to a value less than $+1$. Even this more accurate assumption, as simple as it appears, introduces such complication that a linear solution in analytical form is difficult to obtain.

<u>Case II--Condition A.</u> To introduce the effects of L_L, the leakage inductance, consider the equivalent circuit shown in Figure XVI. For this figure, the Laplace transform of Kirchhoff's voltage equation is

$$31)\quad \left[R + \frac{1}{C_0 s} + L_L s\right] I(s) = \frac{\mu I(s)}{C_0 s} + \frac{E}{s}$$

$$32)\quad I(s) = \frac{E}{L_L\left[s^2 + \frac{R}{L_L}s + \frac{1}{L_L}\left(\frac{1-\mu}{C_0}\right)\right]}$$

Now using 30) again

$$33)\quad E_{g1}(s) = \frac{E}{L_L C_0 s\left[s^2 + \frac{R}{L_L}s + \frac{1}{L_L}\left(\frac{1-\mu}{C_0}\right)\right]}$$

This may be rearranged thus

$$33)\ E_{g_1}(s) = \frac{\epsilon}{L_L C_D s\left\{s + \frac{R}{2L_L} - \left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{1/2}\right\}\left\{s + \frac{R}{2L_L} + \left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{1/2}\right\}}$$

Again using 25) and 26)

$$34)\ E_L(s) = \frac{-\mu\epsilon}{L_L C_D s\left\{s + \frac{R}{2L_L} - \left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{1/2}\right\}\left\{s + \frac{R}{2L_L} + \left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{1/2}\right\}}$$

This is of the form,

$$35)\ E_L(s) = -a_0 \frac{1}{s(s+\alpha)(s+\gamma)}$$

The inverse Laplace transform of 35) is

$$36)\ e_L(t) = -a_0\left[\frac{1}{\alpha\gamma} + \frac{\gamma\epsilon^{-\alpha t} - \alpha\epsilon^{-\gamma t}}{\alpha\gamma(\alpha-\gamma)}\right]$$

By the use of 36) the inverse Laplace transform of 34) is,

$$37)\ e_L(t) = \frac{-\mu\epsilon}{L_L C_D}\left\{\frac{1}{\left(\frac{R}{2L_L} - \left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{1/2}\right)\left(\frac{R}{2L_L} + \left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{1/2}\right)}\right.$$

$$+\left(\frac{R}{2L_L} + \left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{1/2}\right)\epsilon^{-\left(\frac{R}{2L_L} - \left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{1/2}\right)t}$$

$$-\left(\frac{R}{2L_L} - \left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{1/2}\right)\epsilon^{-\left(\frac{R}{2L_L} + \left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{1/2}\right)t}$$

This must be transformed thus

$$93)\quad E_g(s) = \frac{t}{L_1C_0 s\left\{s+\frac{R}{2L_1}-\left[\left(\frac{R}{2L_1}\right)^2-\frac{1-\mu}{L_1C_0}\right]^{1/2}\right\}\left\{s+\frac{R}{2L_1}+\left[\left(\frac{R}{2L_1}\right)^2-\frac{1-\mu}{L_1C_0}\right]^{1/2}\right\}}$$

Substituting 93 and 80

$$94)\quad E_t(s) = \frac{-\mu t}{L_1C_0 s\left\{s+\frac{R}{2L_1}-\left[\left(\frac{R}{2L_1}\right)^2-\frac{1-\mu}{L_1C_0}\right]^{1/2}\right\}\left\{s+\frac{R}{2L_1}+\left[\left(\frac{R}{2L_1}\right)^2-\frac{1-\mu}{L_1C_0}\right]^{1/2}\right\}}$$

This is of the form,

$$95)\quad E_t(s) = -a_0\frac{1}{s(s+\alpha)(s+\gamma)}$$

The inverse Laplace transform of 95 is

$$96)\quad e_t(t) = -a_0\left[\frac{1}{\alpha\gamma}+\frac{\gamma e^{-\alpha t}-\alpha e^{-\gamma t}}{\alpha\gamma(\alpha-\gamma)}\right]$$

By the use of 96 the inverse Laplace transform of 94 is,

$$97)\quad e_t(t) = \frac{-\mu t}{L_1C_0}\left\{\frac{1}{\left(\frac{R}{2L_1}-\left[\left(\frac{R}{2L_1}\right)^2-\frac{1-\mu}{L_1C_0}\right]^{1/2}\right)\left(\frac{R}{2L_1}+\left[\left(\frac{R}{2L_1}\right)^2-\frac{1-\mu}{L_1C_0}\right]^{1/2}\right)}\right.$$

$$+\,\epsilon^{-\left(\frac{R}{2L_1}-\left[\left(\frac{R}{2L_1}\right)^2-\frac{1-\mu}{L_1C_0}\right]^{1/2}\right)t}\left(\frac{R}{2L_1}+\left[\left(\frac{R}{2L_1}\right)^2-\frac{1-\mu}{L_1C_0}\right]^{1/2}\right)-$$

$$-\,\epsilon^{-\left(\frac{R}{2L_1}+\left[\left(\frac{R}{2L_1}\right)^2-\frac{1-\mu}{L_1C_0}\right]^{1/2}\right)t}\left(\frac{R}{2L_1}-\left[\left(\frac{R}{2L_1}\right)^2-\frac{1-\mu}{L_1C_0}\right]^{1/2}\right)-$$

37) cont'd.

$$\div \left(\frac{R}{2L_L} - \left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{\frac{1}{2}}\right)\left(\frac{R}{2L_L} + \left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{\frac{1}{2}}\right)\left[\left(\frac{R}{2L_L} - \left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{\frac{1}{2}}\right) - \left(\frac{R}{2L_L} + \left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{\frac{1}{2}}\right)\right]\Bigg\}$$

Now if $\mu > 1$ the first exponential term in 37) has a positive exponent and regeneration occurs. By use of the hyperbolic functions 37) may be rewritten

$$38)\quad e_b(t) = \frac{\mu E}{\mu - 1}\left[1 - \varepsilon^{-\frac{R}{L_L}t}\left\{\frac{R}{2L_L}\sinh\left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{\frac{1}{2}}t + \left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{\frac{1}{2}}\cosh\left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{\frac{1}{2}}t\right\} \div \left\{\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right\}^{\frac{1}{2}}\right]$$

The output of the generator is given by 38) until $|e_b| = E_{bb}$, when it is assumed that μ suddenly becomes less than $+1$ and $|e_b|$ levels off at the top of the pulse.

37) cont'd.

$$\div\left(\frac{R}{2L}-\left[\left(\frac{R}{2L}\right)^2-\frac{1-\mu}{LC_0}\right]^{1/2}\right)\left(\frac{R}{2L}+\left[\left(\frac{R}{2L}\right)^2-\frac{1-\mu}{LC_0}\right]^{1/2}\right)\Bigg]\Bigg]-\frac{R}{2L}$$

$$\left[\left(\frac{R}{2L}\right)^2-\frac{1-\mu}{LC_0}\right]^{1/2}-\left(\frac{R}{2L}+\left[\left(\frac{R}{2L}\right)^2-\frac{1-\mu}{LC_0}\right]^{1/2}\right)\Bigg)\Bigg]\Bigg\}$$

Now if $\mu > 1$ the first exponential term in 37) has a positive exponent and regeneration occurs. By use of the hyperbolic functions 37) may be rewritten

38) $$e_t(t)=\frac{\mu E}{\mu-1}\left[1-e^{-\frac{R}{2L}t}\left\{\frac{R}{2L}\sinh\left[\left(\frac{R}{2L}\right)^2-\frac{1-\mu}{LC_0}\right]^{1/2}t+\left[\left(\frac{R}{2L}\right)^2-\frac{1-\mu}{LC_0}\right]^{1/2}\cosh\left[\left(\frac{R}{2L}\right)^2-\frac{1-\mu}{LC_0}\right]^{1/2}t\right\}\div\left[\left\{\left(\frac{R}{2L}\right)^2-\frac{1-\mu}{LC_0}\right\}^{1/2}\right]\right.$$

The output of the generator is given by 38) until $|e_t| = E_{tt}$, when it is assumed that μ suddenly decreases less than 1 and $|e_t|$ levels off at the top of the pulse.

Condition B. The special conditions that R is small enough and L_L and μ large enough so that

$$39)\quad \frac{\mu - 1}{L_L C_D} >> \left(\frac{R}{2L_L}\right)^2$$

then in equation 38)

$$40)\quad \frac{\mu}{\mu - 1} \longrightarrow 1$$

$$41)\quad \varepsilon^{-\frac{R}{2L_L}t} \longrightarrow \varepsilon^{0t} = 1$$

$$42)\quad \frac{R/2L_L}{\left[\left(\frac{R}{2L_L}\right)^2 - \frac{1-\mu}{L_L C_D}\right]^{\frac{1}{2}}} \longrightarrow 0$$

$$43)\quad \frac{R}{2L_L} \longrightarrow 0$$

and equation 38) may be written

$$44)\quad e_o(t) \approx E\left[1 - \cosh\left(\frac{\mu}{L_L C_D}\right)^{\frac{1}{2}} t\right]$$

In this special case 44) gives the output of the generator during the rise of the pulse.

Case III. Now to study the circuit in Figure XI when C is not equal to zero and R is so large that its effect is negligible compared to that of C. In this case, the effect of r_p is considered. These are all included in the equivalent circuit of Figure XVII.

Following the same scheme as in the two previous cases write:

$$45)\quad \left[r_p + L_L S + \frac{1}{S}\left(\frac{1}{C} + \frac{1}{C_D} \right)\right] I(s) = \mu E_{g_1}(s) + \frac{\epsilon}{S} = \frac{\mu I(s)}{C_D S} + \frac{\epsilon}{S}$$

and

$$46)\quad I(s) = \frac{\epsilon}{L_L\left[S^2 + \frac{r_p}{L_L} S + \frac{1}{L_L}\left(\frac{1}{C} + \frac{1-\mu}{C_D} \right)\right]}$$

Again using 21)

$$47)\quad \mu E_{g_1}(s) = \frac{\mu\epsilon}{C_D L_L S\left[S^2 + \frac{r_p}{L_L} S + \frac{1}{L_L}\left(\frac{1}{C} + \frac{1-\mu}{C_D} \right)\right]}$$

This may be rearranged in a manner analogous to the rearranging of 30) in the form of 32). After this rearrangement equations 35) and 36) again hold where

$$48)\quad a_0 = \frac{\mu\epsilon}{L_L C_D}$$

$$\alpha = \frac{r_p}{2L_L} - \left[\left(\frac{r_p}{2L_L} \right)^2 - \frac{1}{L_L}\left(\frac{1}{C} + \frac{1-\mu}{C_D} \right)\right]^{\frac{1}{2}}$$

$$\gamma = \frac{r_p}{2L_L} + \left[\left(\frac{r_p}{2L_L} \right)^2 - \frac{1}{L_L}\left(\frac{1}{C} + \frac{1-\mu}{C_D} \right)\right]^{\frac{1}{2}}$$

In order that one of the exponential terms in 36) have a positive exponent, α or γ must be negative. It is necessary that some condition be imposed upon the

quantity $\frac{1}{L_L}\left(\frac{1}{C} + \frac{1-\mu}{C_D}\right)$ in α and/or γ since $\frac{r_p}{2L_L}$ is positive and becomes negative when $\varepsilon^{-\alpha \text{ or } \gamma t}$ is written. Clearly a positive exponent is obtained from this portion of α in 48) if,

49) $$\frac{1}{C} + \frac{1-\mu}{C_D} < 0$$

or

50) $$\mu > \frac{C_D}{C} + 1 .$$

Since the effect of r_p is being considered; ie. $r_p \neq 0$

51) $$e_b(t) = -\mu e_{g_1}(t) + i(t) r_p$$

and

52) $$E_b(s) = -\mu E_{g_1}(s) + I(s) r_p$$

Referring to 46) which, like 47), may be rearranged in a manner similar to 33) and to 47) the Laplace transform of 52) takes the form

53) $$E_b(s) = \frac{-a_0}{s(s+\alpha)(s+\gamma)} + \frac{a_1}{(s+\alpha)(s+\gamma)}$$

where

54) $$a_1 = \frac{r_p \varepsilon}{L_L}$$

and a_0, α, and γ are given by 48)

The inverse Laplace transform of 53) is

55) $$e_b(t) = -a_0\left[\frac{1}{\alpha\gamma} + \frac{\gamma\varepsilon^{-\alpha t} - \alpha\varepsilon^{-\gamma t}}{\alpha\gamma(\alpha-\gamma)}\right] + a_1\left[\frac{\varepsilon^{-\alpha t} - \varepsilon^{-\gamma t}}{\gamma - \alpha}\right]$$

quantity $\frac{1}{\mu}\left(\frac{1}{c} + \frac{1-\mu}{c_0}\right)$ in α and/or γ since $\frac{\lambda_p}{\lambda\mu}$ is positive and becomes negative when $e^{-\alpha t \text{ or } \gamma t}$ is written. Clearly a positive exponent is obtained from this portion of α in 48) if,

$$49) \quad \frac{1}{c} + \frac{1-\mu}{c_0} < 0$$

or

$$50) \quad \mu > \frac{c_0}{c} + 1 .$$

Since the effect of λ_p is being considered; ie. $\lambda_p \neq 0$

$$51) \quad e_f(t) = -\mu\, e_{g_1}(t) + i(t)\, \lambda_p$$

and

$$52) \quad E_f(s) = -\mu\, E_{g_1}(s) + I(s)\, \lambda_p$$

Referring to 48) which, like 47), may be rearranged in a manner similar to 31) and to 47) the Laplace transform of 52) takes the form

$$53) \quad E_f(s) = \frac{-a_0}{s(s+\alpha)(s+\gamma)} + \frac{a_1}{(s+\alpha)(s+\gamma)}$$

where

$$54) \quad a_1 = \frac{\lambda_p E}{\lambda\mu}$$

and a_0, α, and γ are given by 48)

The inverse Laplace transform of 53) is

$$55) \quad e_f(t) = -a_0\left[\frac{1}{\alpha\gamma} + \frac{\alpha e^{-\gamma t} - \gamma e^{-\alpha t}}{\alpha\gamma(\gamma-\alpha)}\right] + a_1\left[\frac{e^{-\alpha t} - e^{-\gamma t}}{\gamma - \alpha}\right]$$

Two special cases of this general solution for Case III are of interest.

<u>Condition I.</u> The time constant α is determined primarily by C_D and r_p. Then equation 45) is rewritten

$$56)\quad \left[r_p + \frac{1}{s}\left(\frac{1}{C} + \frac{1}{C_D}\right)\right] I(s) = \mu E_{g_1}(s) + \frac{\epsilon}{s} = \frac{\mu I(s)}{C_D\, s} + \frac{\epsilon}{s}$$

and 46) becomes

$$57)\quad I(s) = \frac{\epsilon}{r_p\left[s + \frac{1}{r_p}\left(\frac{1}{C} + \frac{1-\mu}{C_D}\right)\right]}$$

and 47) becomes

$$58)\quad \mu E_{g_1}(s) = \frac{\mu \epsilon}{r_p C_D s\left[s + \frac{1}{r_p}\left(\frac{1}{C} + \frac{1-\mu}{C_D}\right)\right]}$$

Again

$$59)\quad E_b(s) = -\mu E_{g_1}(s) + r_p I(s)$$

and this takes the form

$$60)\quad E_b(s) = \frac{-a_0}{s(s+\alpha)} + \frac{a_1}{s+\alpha}$$

where

$$61)\quad a_0 = \frac{\mu \epsilon}{C_D\, r_p}\,, \quad a_1 = \epsilon$$

Two special cases of this general solution for Case III are of interest.

Condition I. The time constant α is determined primarily by C_g and r_p. Then equation 45) is rewritten

$$56) \quad \left[r_p + \frac{1}{s}\left(\frac{1}{C} + \frac{1}{C_g}\right)\right] I(s) = \mu E_{g_1}(s) + \frac{E}{s} = \frac{\mu I(s)}{C_g s} + \frac{E}{s}$$

and 46) becomes

$$57) \quad I(s) = \frac{E}{r_p\left[s + \frac{1}{r_p}\left(\frac{1}{C} + \frac{1-\mu}{C_g}\right)\right]}$$

and 47) becomes

$$58) \quad \mu E_{g_1}(s) = \frac{\mu E}{r_p C_g s\left[s + \frac{1}{r_p}\left(\frac{1}{C} + \frac{1-\mu}{C_g}\right)\right]}$$

Again

$$59) \quad E_t(s) = -\mu E_{g_1}(s) + r_p I(s)$$

and it takes the form

$$60) \quad E_t(s) = \frac{-a_0}{s(s+\alpha)} + \frac{a_1}{s+\alpha}$$

where

$$61) \quad a_0 = \frac{\mu E}{C_g r_p}, \quad a_1 = E$$

and $\alpha = \frac{1}{r_p}\left(\frac{1}{C} + \frac{1-\mu}{C_D}\right).$

The inverse Laplace transform of 60) is

62) $$e_b(t) = \frac{-a_0}{\alpha}\left(1 - \epsilon^{-\alpha t}\right) + a_1 \epsilon^{-\alpha t}$$

Using 62) and the values given by 61)

63) $$e_b(t) = E\left[\frac{-\mu C}{C(\mu-1) - C_D} + 1\right]\epsilon^{-\frac{1}{r_p}\left(\frac{1}{C} + \frac{1-\mu}{C_D}\right)t} + \frac{\mu E C}{C(\mu-1) - C_D}$$

Equation 63) is an expression for the voltage during the rise of the pulse when the time constant is determined primarily by r_p and C_D. Referring to the exponential term, the quantity $\left(\frac{1}{C} + \frac{1-\mu}{C_D}\right)$ must be negative for regeneration. This term can be negative only if $\frac{1}{C} < \frac{\mu-1}{C_D}$ (or $\mu > \frac{C_D}{C} + 1$). The amount that the quantity $\frac{\mu-1}{C_D}$ will differ from the limiting value $\frac{1}{C}$ is determined by the value of C_D (μ is assumed to be relatively constant over the portion of the cycle under consideration). The product of the negative quantity $\left(\frac{1}{C} + \frac{1-\mu}{C_D}\right)$ and $-\frac{1}{r_p}$ gives the positive exponent required for regeneration. The magnitude of this product depends upon the values of r_p and C_D primarily since the magnitude of $\left(\frac{1}{C} + \frac{1-\mu}{C_D}\right)$ depends upon C_D; the value of C enters as a limiting factor.

<u>Condition II.</u> The time constant α is determined primarily by L_L and C_D. In this case

64) $\alpha = -\gamma$

and equation 55) becomes

65) $$c_b(t) = -a_0\left(\frac{1}{\gamma^2} - \frac{1}{\gamma^2}\cosh\gamma t\right) + \frac{a_1}{\gamma}\sinh\gamma t$$

and using the values from 48) where the terms involving $\frac{r_p}{2L_L}$ are set equal to zero so that 64) is satisfied,

66) $$c_b(t) = E\left(\frac{\mu C}{C(\mu-1)-C_D}\left\{1-\cosh\left[-\frac{1}{L_L}\left(\frac{1}{C}+\frac{1-\mu}{C_D}\right)\right]^{\frac{1}{2}} t\right\} + \frac{r_p(L_L C_D)^{\frac{1}{2}}}{L_L}\left[\frac{C}{C(\mu-1)-C_D}\right]^{\frac{1}{2}}\left\{\sinh\left[-\frac{1}{L_L}\left(\frac{1}{C}+\frac{1-\mu}{C_D}\right)\right]^{\frac{1}{2}} t\right\}\right)$$

With the time constant α determined primarily by the factors indicated in condition II, above, the rise of the pulse is given by equation 66).

<u>The Top of the Pulse.</u> With the rise of the pulse completed the behavior of the circuit is now described for the top of the pulse. This is the period of time in which the top of the pulse is relatively flat. It will be recalled that μ is assumed to be greater than $+1$ as long as the magnitude of the output is less than E_{bb} and $c_g \geq 0$. As soon as the magnitude of the output reaches E_{bb}, μ is assumed to become less

Condition II. The time constant α is determined primarily by L_p and C_p. In this case

(64) $\alpha = -\gamma$

and equation (58) becomes

$$(65)\quad C_o(t) = -a_0\left(\frac{1}{\gamma_1} - \frac{1}{\gamma^2}\cosh\gamma t\right) + \frac{a_1}{\gamma}\sinh\gamma t$$

and using the values from (40) where the terms involving $\frac{d\mu}{dt}$ are set equal to zero so that (64) is satisfied,

$$(66)\quad C_g(t) = E\left(\frac{\mu C}{C(\mu-1)-C_0}\right)\left\{1-\cosh\left[\frac{1}{L_p}\left(\frac{1}{C}+\frac{1-\mu}{C_0}\right)\right]^{\frac{1}{2}}t\right\}$$

$$+\frac{\dot{e}_g(L_pC_g)}{L_p}\left[\frac{C}{C(\mu-1)-C_0}\right]^{\frac{1}{2}}\left\{\sinh\left[\frac{1}{L_p}\left(\frac{1}{C}+\frac{1-\mu}{C_0}\right)\right]^{\frac{1}{2}}t\right\}$$

With the time constant α determined primarily by the factors indicated in condition II, above, the rise of the pulse is given by equation (66).

The Top of the Pulse. With the rise of the pulse completed the behavior of the circuit is now described for the top of the pulse. This is the period of time in which the top of the pulse is relatively flat. It will be recalled that μ is assumed to be greater than $+1$ as long as the magnitude of the output is less than E_{bb} and $e_g = 0$. As soon as the magnitude of the output reaches E_{bb}, μ is reduced to less than

than $+1$. $|e_b|$, however, is assumed to remain equal to E_{bb} until $e_g \leq 0$. Again an equivalent circuit is made for Figure XI; this equivalent circuit is shown in Figure XVIII. Once again, simplifying assumptions are made.

These assumptions are: a) that the initial voltage on C, which was E_{co} at the beginning of the rise, is still E_{co}, b) that the initial current in L_p is negligible, c) that the effect of L_1 may be neglected. With these assumptions two conditions may be considered.

Case I. C is so large that the pulse is terminated by L_p above. Neglecting the current through r_g a simple RL circuit results and

67) $$e_b(t) = -E_{bb}\ \varepsilon^{-\frac{r_p}{L_p}t}$$

Since there is no appreciable voltage developed across C,

68) $$E_c \cong E_{co}$$

and

69) $$-e_g = e_b - E_{co}$$

Now when $e_g = 0$, from 69)

70) $$e_b = E_{co}$$

and μ once more becomes $\geq +1$ and regeneration again takes place, this time however, cutting the tube off.

So then one may write, using 67) and 70)

$$71)\quad |E_{co}| = E_{bb}\,\varepsilon^{-\frac{r_p}{L_p}\tau_m}$$

where τ_m is the maximum pulse duration that this pulse transformer circuit can produce. Solving for τ_m

$$72)\quad \tau_m = \frac{L_p}{r_p}\;\frac{E_{bb}}{|E_{co}|} = \frac{L_p}{r_p}\,\ln \mu .$$

Because of the simplifying assumptions made the actual pulse width would be less than indicated by 72).

<u>Case II</u>. L_p is large, the effect of C_p is negligible when $e_g > 0$ and C is so small that the duration of the pulse is determined by C. Even though small, C must be large enough to keep the initial voltage value at the beginning of the top of the pulse, E_{co}.

With the switch closed in Figure XVIII

$$73)\quad e_g(t) = \frac{\left(E_{bb} - |E_{co}|\right)}{r_p + r_g}\, r_g\, \varepsilon^{\frac{-t}{(r_g + r_p)C}}$$

So then $e_g \to 0$ and a very small current rise in L_p is sufficient to make $e_g = 0$ thus terminating the pulse.

The maximum pulse duration in this case is given approximately,

$$74)\quad \tau_m = (r_p + r_g)\, C.$$

<u>The Tail of the Pulse.</u> The behavior of the circuit during this time may be considered in two parts. The equivalent circuit is as shown in Figure XIX. The first part of this action involves that portion of the pulse where the grid voltage proceeds to its maximum negative value from its initial value of E_{co}. It is here assumed that C is finite and hence that the pulse actually has a flat top and very little oscillation on the tail. The variation of e_b depends during this time upon the circuit parameters shown in Figure XIX as well as the initial charge on C_D and the initial current in L_p. It should be noted that the circuit has proceeded to regenerate to cutoff from the point at the end of the top of the pulse where $e_g = 0$. That is, at the outset of the first part of the final action $e_g = E_{co}$.

While the variation on e_b could be determined by writing the equation for the first part of the final action, this variation is of small interest compared to that of e_c during the second part of this final action. This second part of the action involves the discharge of C, through R, from its value when e_g is at its maximum negative value to its value when $e_g = E_{co}$. If the voltage across C at the beginning of this part of the final action is denoted by V_c, this value usually

The Tail of the Pulse. The behavior of the circuit during this time may be considered in two parts. The equivalent circuit is as shown in Figure XIX. The first part of this motion involves that portion of the pulse where the grid voltage proceeds to its maximum negative value from its initial value of E_{co}. It is here assumed that C is finite and hence that the pulse actually has a flat top and very little oscillation on the tail. The variation of e_g depends during this time upon the circuit parameters shown in Figure XIX as well as the initial charge on C_g and the initial current in L_p. It should be noted that the circuit has proceeded to momentarily to cutoff from the point at the end of the top of the pulse where $e_g = 0$. That is, at the outset of the first part of the final motion $e_g = E_{co}$.

While the variation on e_c as it be determined by writing the equation for the first part of the final motion, this variation is of small interest compared to that of e_c during the second part of this final motion. This second part of the motion involves the discharge of C, through R, from the value when e_g is at its maximum negative value to the value when $e_g = E_{co}$. If the voltage across C at the beginning of this part of [illegible] the plate motion is [illegible] by e_{g1}, this value normally being about -0.5 to -0.8 E_{bb}, then the voltage across C at any time thereafter until conduction again starts is given by

75 $$e_c = E_{co} - (V_c - E_c)\,\varepsilon^{-t/RC}$$

and

76) $$e_g = e_b + e_c$$

Equation 75) is the ordinary type of RC discharge equation and the time of discharge can be controlled by the values of R and C. This shows mathematically that the time interval between pulses is determined by the R_gC_g time constant as has previously been asserted qualitatively. In the case discussed above where the pulse duration is primarily determined by C_g (the top of the pulse CaseII) it is now apparent that the pulse recurrence frequency is determined largely by the values of R_g and C_g, since the time interval between pulses is always dependent upon R_g and C_g and in this case the duration of the pulse, as well, depends largely upon C_g. This has neglected the time of rise and time of fall of the pulse. There is the condition where the time of rise---condition I Case III, Rise of Pulse---is more dependent upon C_g than any specific circuit parameter but even then the effect of C_g is minor compared to the effect of C_p. (Refer specifically to the exponential being about -0.5 to -0.8 E_{cc}, then the voltage across C at any time thereafter until conduction again starts is given by

$$75) \quad e_c = E_{co} - (V_c - E_c)\,\varepsilon^{-t/RC}$$

and

$$76) \quad e_g = e_r + e_c$$

Equation 75) is the ordinary type of RC discharge equation and the time of discharge can be controlled by the values of R and C. This shows mathematically that the time interval between pulses is determined by the R_gC_g time constant as has previously been accepted qualitatively. In the case discussed above where the pulse duration is primarily determined by C_g (the top of the pulse itself) it is now apparent that the pulse recurrence frequency is determined largely by the values of R_g and C_g, since the time interval between pulses is always dependent upon R_g and C_g and in this case the duration of the pulse, as well, depends largely upon C_g. This has neglected the time of rise and time of fall of the pulse. There is the condition where the time of rise--condition I Case III, Rise of Pulse--is more dependent upon R_g than any specific circuit parameter but even then the effect of R_g is minor compared to the effect of C_g. (Refer specifically to the experimental term of equation 63). In any case, the time of rise and fall of the pulse are small compared to the time of the pulse plus the time interval between pulses.

The implication here is not that the time of rise and time of fall cannot be large but that, in practice, they are not usually large. That is, circuit parameters are used which make the pulse rise and fall sharply. A brief look at the equations representing the behavior of the circuit during rise of the pulse will reveal that in every case the pulse transformer is involved. In some cases C_D, the distributed capacity of the transformer, appears without L_L; in some cases both appear. Likewise, a brief reference to the portion devoted to the tail of the pulse will show that the transformer parameters are involved in how the instantaneous plate voltage varies after the pulse itself has terminated. Furthermore, the transformer parameters are involved not only in the rise and fall of the pulse but in its duration (refer to equation 67). Thus, it is borne out that the operation of the single swing blocking oscillator, as it differs from the multiple swing blocking oscillator, depends to a great extent upon the iron core transformer and to some extent upon the values of R_g and C_g.

[illegible] [illegible] [illegible]. [illegible] the [illegible]
[illegible] of the [illegible]
of the voice [illegible]

The illustration here [illegible]
and [illegible] of [illegible]
they are [illegible]
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A [illegible] of the [illegible]
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that in every case the [illegible]
In more detail, the [illegible]
[illegible]
[illegible], a [illegible]
the tail of the [illegible]
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[illegible]
[illegible]
[illegible]
[illegible]

Throughout the entire discussion of the single swing blocking oscillator the question of tube selection and desirable tube characteristics has largely been ignored. It has been tacitly assumed that such a tube is employed in the circuits described that will allow the circuits to operate as indicated. It is important to note that a triode is indicated in the circuit diagram for triodes are used in many applications. It is the aim of the next section of this paper to discuss not only the design considerations of the pulse transformer and the R_gC_g combination but the tube requirements as well, since the output waveform depends upon all of these.

DESIGN CONSIDERATIONS FOR SELECTION OF CIRCUIT COMPONENTS

<u>The Pulse Transformer</u>. In general it can be said that the pulse transformer must have both high and low frequency response sufficient to give the desired output waveform. The rates of rise and fall of the pulse are determined by its high frequency response and the pulse duration by its low frequency response. Reference to equation 44) illustrates that pulse rise depends upon $\sqrt{L_L C_D}$ and it can be shown that pulse fall depends upon L_p and C_D. While the shape of the pulse is now known to be dependent upon these parameters of the pulse

Throughout the entire discussion of the single swing blocking oscillator the question of tube selection and desirable tube characteristics has largely been ignored. It has been tacitly assumed that such a tube is employed in the circuits described that will allow the circuits to operate as indicated. It is important to note that a triode is indicated in the circuit diagram for triodes are used in many applications. It is the aim of the next section of this paper to discuss not only the design considerations of the pulse transformer and the R_gC_g combination but the tube requirements as well, since the output waveform depends upon all of these.

[illegible] DETERMINATION AND DESIGN OF CIRCUIT COMPONENTS

The Pulse Transformer. In general it can be said that the pulse transformer must have both high and low frequency response sufficient to give the desired output waveform. The rates of rise and fall of the pulse are determined by its high frequency response and the pulse duration by its low frequency response. Reference to equation (4) illustrates that pulse duration depends upon $\sqrt{LC}$ and it can be shown that pulse shape depends [illegible] and [illegible]. While the shape of the pulse is now [illegible] of the pulse [illegible] transformer, as well as the other circuit parameters and the tube, it is appropriate to ask how one would like to have these parameters shape the pulse. In other words; what constitutes the optimum pulse shape? For any specific problem at hand this question could be answered concisely but for the general problem the answer would be controversial. In general a good pulse shape is a compromise among high rate of rise, low overshoot, small droop of the top of the pulse, high rate of fall and low backswing voltage on the tail of the pulse. Along with producing a good pulse shape the transformer should effect the maximum transfer of energy between plate and grid circuits. For a given τ, pulse duration, and R_l it has been found that maximum energy transfer and good pulse shape result if:

77 a) $Z_T = \sqrt{\frac{L_L}{C_D}} = R_\ell$ OR $\frac{1}{2} L_L I_\ell^2 = \frac{1}{2} C_D V_\ell^2$

b) $\alpha = \beta$ OR $\sqrt{2L_p C_D} \cong \sqrt{2L_e C_D} \triangleq \tau = \tau_{opt}$

c) $(\alpha + \beta)_{opt} = \sqrt{\frac{2L_L}{L_e}} + \frac{1}{R_e}\sqrt{\frac{L_L}{C_D}} \cong \sqrt{\frac{2L_L}{L_p}} =$

a minimum, where

78) $$\alpha \triangleq \frac{\text{Energy flowing into core during the pulse}}{\text{Energy transmitted to load during the pulse}} = \frac{V_\ell \tau}{2 I_\ell L_p}$$

transformer, as well as the other circuit parameters and the tube, it is appropriate to ask how one would like to have these parameters shape the pulse. In other words, what constitutes the optimum pulse shape for any specific problem at hand? This question could be answered completely but for the general problem the answer would be controversial. In general a good pulse shape is a compromise among high rate of rise, low overshoot, small droop of the top of the pulse, high rate of fall and low backswing voltage on the tail of the pulse. Along with producing a good pulse shape the transformer should effect the maximum transfer of energy between plate and grid circuits. For a given T, pulse duration, and R_L it has been found that maximum energy transfer and good pulse shape result if:

77 a) $Z_T = \sqrt{\frac{L_e}{C_D}} = R_L$ or $\frac{1}{2} L_e I_e^2 = \frac{1}{2} C_D V_2^2$

b) $\alpha = \beta$ or $\sqrt{2 L_p C_L} \cong \sqrt{2 L_e C_D} \triangleq T = T_{opt}$

c) $(\alpha + \beta)_{opt} = \sqrt{\frac{2L_e}{L_p}} + \frac{1}{R_L}\sqrt{\frac{L_e}{C_D}} \cong \sqrt{\frac{2L_e}{L_p}} =$

a minimum, where

78) $\rho \triangleq \dfrac{\text{Energy stored in } L_p \text{ during the pulse}}{\text{Energy transmitted to load during the pulse}} = \dfrac{V_2 T}{2 L_e L_p}$

78) $\beta \triangleq \dfrac{\text{Energy stored in leakage inductance and distributed capacitance during the pulse}}{\text{Energy transmitted to the load during the pulse}} = \dfrac{\frac{1}{2} L_L I_l + \frac{1}{2} C_D V_l^2}{V_l I_l \tau}$

and where

Z_T is the characteristic impedance of secondary winding

R_l is the load impedance (a resistance)

L_L is the leakage inductance

C_D is the distributed capacity (effective)

L_p is the primary inductance

L_e is the effective shunt inductance (primary)

R_e is the effective shunt resistance (primary)

I_l is the current through the load

V_l is the voltage across the load

The design of the pulse transformer is approached with a view to approximating the optimum design, rather than achieving it exactly. The exact method of approach, wherein α and β are expressed as functions of the number of turns, voltage on the high voltage winding, wire diameter, etc., and $(\alpha + \beta)_{opt}$ is made a minimum, yields optimum design but the solution of a high degree algebraic equation is required. Rather than go through this laborious process, one may use the criteria of 77a) and b) as constraints upon the design and then make an estimate based upon experience and recorded experimental

data as to the optimum flux density, number of turns or the core volume. The resultant transformer will then surely satisfy 77a) and b) and may satisfy 77c) but it need not. If it does not come near enough to satisfying 77c) to give satisfactory performance, then a new estimate of flux density, number of turns, or core volume must be made and again $(\alpha + \beta)_{opt}$ either measured or calculated. This process is continued until the design is found which satisfies, by measurement as well as by calculation, 77a), b), and c) and which operates satisfactorily in the intended circuit.

To carry out the above mentioned procedure, suppose that a transformer with single layer windings for primary and secondary is to be sought; then,

81) $C_D = \dfrac{0.0885\, \epsilon\, \mathcal{U}\, \mathcal{L} \cdot 10^{-12}}{\Delta}$ farads

82) $L_L = \dfrac{4\pi N^2 \Delta\, \mathcal{U}}{10^9\, \mathcal{L}}$ henrys and

83) $L_p = \dfrac{4\pi N^2 A \mu_e}{10^9\, l}$ henrys

where

84) $\mathcal{U}$ is the mean perimeter of the coil

ϵ is the dielectic constant of insulation

84) Cont'd.

$\mathcal{L}$ is the length of winding

ℓ is the mean length of magnetic path

A is the core cross sectional area

μ_e is the effective pulse permeability of core material

Δ is the spacing between primary and secondary in centimeters

By satisfying 77a), that is,

85) $$R_\ell = \sqrt{\frac{L_L}{C_D}}$$

through the use of 81) and 82) it is found that

86) $$\Delta = \frac{R_\ell \mathcal{L} \sqrt{\epsilon}}{377 N}$$

By satisfying 77b), that is,

87) $$\tau = \tau_{opt} = \sqrt{2 L_p C_D}$$

through the use of 81) and 83) it is found that

88) $$\tau^2 = \frac{84 \times 10^{-20}}{R_\ell} \mu_e \sqrt{\epsilon} \; N^3 \frac{A\mathcal{U}}{\ell} .$$

Assuming now that a specific type of standard core is to be used, or, if not, that the volume of the core and type of material are chosen, all quantities in 88) will be at hand except N, τ and R_ℓ; the

quantity $\frac{A\mathcal{U}}{\ell}$ can be expressed as a multiple of one dimension of the core since, for minimum space, the hole in the core should be filled with the coil and the hole in the coil should be filled by one side of the core. The value of η will be dictated by the particular application and an approximation, at least, can be had for R_1 from the intended circuit. So then, the value of N may be computed from 88).

The wire size is now chosen. Since the average power dissipation is usually negligibly small as far as permissable temperature rise is concerned, the size of wire is not critical from the temperature rise viewpoint. The size is therefore chosen to give ease of winding keeping in mind the core window size and the requirement that the winding resistance be negligible compared to the load resistance, R_1. With the size of wire determined, $\mathcal{L}$ may be calculated.

Using the value of $\mathcal{L}$ the values of Δ, C_p, L_L, and L_p may be calculated from 86), 81), 82), and 83) respectively. Following this the quality design test may be made by calculation from 77c), which is:

89) $(\alpha + \beta)_{opt} \cong \sqrt{\frac{3L_L}{L_p}}$ = a minimum

If the value in 89) turns out to be too large or if the transformer fails to operate satisfactorily

the entire process may be repeated for a different core volume until a satisfactory transformer is obtained.

In carrying out the design of a pulse transformer above, specific attention was given to the two salient characteristics of the transformer; its pass band and the turns ratio. In this design leakage inductance and distributed capacity are functions of the dimensions of the coil and the core and of the material of both. It was previously shown that the rise and fall of the pulse is a function of L_L, C_D, and L_P.

Certain construction features also contribute to a close control of the leakage inductance and distributed capacity. The leakage inductance can be minimized by a large coefficient of coupling and as few turns as possible. Both the primary and secondary windings should be on the same coreleg; if both core legs are used the primary and secondary windings should both be split and part of each wound on both legs. For the maximum rates of rise and fall of the pulse, single layer windings should be used.

The capacitance may be reduced by increasing the thickness of the insulation between the windings or between the windings and the core. This, however, increases the entire process may be repeated for a different core volume until a satisfactory transformer is obtained.

In carrying out the design of a pulse transformer above, specific attention was given to the two salient characteristics of the transformer; its pass band and the turns ratio. In this design leakage inductance and distributed capacity are functions of the dimensions of the coil and the core and of the material of both. It was previously shown that the rise and fall of the pulse is a function of L_L, C_D, and L_P.

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The capacitance may be reduced by increasing the thickness of the insulation between the windings or between the windings and the core. This, however, increases the leakage inductance and the value of LC remains relatively constant so that the pulse shape is not affected greatly.

In order that the transformer have good high frequency response, with the provision that the core does not saturate, a high effective permeability is required. One method to increase the effective permeability is to decrease the thickness of the core laminations. There is a limit to this since it is impossible to roll laminations thinner than one mil without upsetting the crystalline structure of the steel necessary for high permeability.

A particular construction feature that has been found to increase the pulse duration is the insertion of an air gap in the core. The reason for this result is not well understood. It may be reasonably well explained by considering that the core losses are quite high and that the L/R time constant is effectively increased by decreasing R more than L is decreased with insertion of the air gap.

In general, if maximum pulse duration is desired from a particular transformer a step down ratio should be used. This permits the use of more of the available plate winding turns, thus increasing the inductance of the leakage inductance and the value of LC remains relatively constant so that the pulse shape is not affected greatly.

In order that the transformer have good high frequency response, with the provision that the core does not saturate, a high effective permeability is required. One method to increase the effective permeability is to decrease the thickness of the core laminations. There is a limit to this since it is impossible to roll laminations thinner than one mil without upsetting the crystalline structure of the steel necessary for high permeability.

A particular construction feature that has been found to improve the pulse duration is the insertion of an air gap in the core. The reason for this result is not well understood. It may be reasonably well explained by considering that the core losses are quite high and that the L/R time constant is effectively increased by decreasing R more than L is decreased with insertion of the air gap.

In general, if maximum pulse duration is desired from a particular transformer a step down ratio should be used. This permits the use of more of the available winding space, thus increasing the inductances of this winding. In all cases, however, it is neither possible nor desirable to use a step down in going from the plate to grid. In certain cases the question of whether a step up or step down is to be used may be dictated by the tube to be used in the circuit.

<u>The Tube</u>.(19) With low μ triodes, if maximum peak pulse current is desired the turns ratio should be adjusted so that the plate output impedance is about equal to the grid input impedance; this usually implies a step up. With tetrodes, on the other hand, a step down is required since the grid current becomes equal to the plate current at very low values of positive grid potentials.

It is seen from this that the operation of triodes and tetrodes or pentodes in the blocking oscillator circuit is apt to be quite different. This is further brought out by considering the tube characteristics of a triode section of the 6SN7 and those of the 6AC7, a pentode. These are shown in Figures XX and XXI respectively. Typical of medium μ triodes, the 6SN7 exhibits a large power gain in the positive grid region. For example, $\partial I_p / \partial I_g = 3$ when the grid is driven from plus 50 to plus 75 volts with $E_p = 150$. In contrast, the 6AC7 characteristics show that as soon as grid current starts to flow $\partial I_p / \partial I_g$ becomes less than 1.

this winding. In all cases, however, it is neither possible nor desirable to use a step down in going from the plate to grid. In certain cases the question of whether a step up or step down is to be used may be dictated by the tube to be used in the circuit.

(17)

The Tube. With low μ triodes, if maximum peak plate current is desired the turns ratio should be adjusted so that the plate output impedance is about equal to the grid input impedance; this usually implies a step up. With tetrodes, on the other hand, a step down is required since the grid current becomes equal to the plate current at very low values of positive grid potentials.

It is seen from this that the operation of triodes and tetrodes or pentodes in the blocking oscillator circuit is apt to be quite different. This is further brought out by considering the tube characteristics of a triode section of the [illegible] and those of the [illegible], a pentode. These are shown in Figures [illegible] and [illegible] respectively. [illegible] μ triodes, the [illegible] [illegible] positive grid region. [illegible] $\partial I_p / \partial I_g = 3$ [illegible] with $E_p = 150$. In contrast, [illegible] $\partial I_p, \partial I_g$ [illegible].

For example, at a grid voltage of plus 25 volts $\frac{\partial E_g}{\partial I_g} << 1$. Thus, while the peak current obtainable from a triode is limited by the point at which more power is dissipated in the grid circuit than can be supplied, the peak current from the pentode is limited to that obtainable near zero bias. If a high energy output pulse is required, the triode would probably be chosen because it not only has a large value of $\frac{\partial I_p}{\partial I_g}$ over the portion of the characteristics corresponding to the peak of the pulse but a large value of I_p, $\frac{\partial E_g}{\partial I_g}$ and a small r_p. If a short pulse with steep sides and relatively low energy is desired then a pentode connected as a triode would be used since the g_m of the pentode is higher, and there is sufficient gain for regeneration with transformers of low inductance. For even greater energy in the output pulse than that afforded by the triode a beam power tetrode may be connected as a triode. It will handle a pulse of greater energy because of its larger dissipation rating.

No matter what type of tube is used the average manufacturer's specifications should not be exceeded. If the grid dissipation rating is exceeded, grid emission may follow with the result that the grid remains positive after the pulse. The heavy grid current that

results may destroy the tube. If the emission rating is exceeded loss of emission is apt to result with a consequent droop in the top of the pulse.

The effect of the tube in shaping the pulse is brought about by the limiting action of the tube that causes the quasi-stable state---the temporary stable state that exists during the top of the pulse. If the quasi-stable state is brought about by a heavy grid current where r_p is high, the case of current limiting, a rectangular current pulse will be produced. If the quasi-stable state is brought about by voltage limiting---"bottoming" of the plate---a rectangular voltage pulse will result. The effect of the tube in producing a short or long pulse has already been indicated in connection with the transformer ratio.

The R_gC_g Combination. As previously shown in the semi-mathematical description of the operation, the interval between pulses is determined by the value of C_g and R_g. It was shown, too, that if C_g is excessively large the pulse is terminated by the low frequency response of the transformer---see CASE I, Top of the Pulse, above. If the highest possible ratio of pulse duration to time of rise and fall is desired then C_g should be made very large. If C_g is smaller it will decrease the [illegible] may destroy the tube. If the radiation [illegible] is measured [illegible] of the tube.

The effect of the tube is [illegible] magnetic [illegible] of the tube [illegible] If the [illegible]

[illegible] The effect of the [illegible] is [illegible]

The L.C. Oscillation. [illegible]

magnitude of the pulse and decrease the slope of the sides. If C_g is reduced to a great extent the pulse shape approaches a sinusoid. The values of R_g and C_g may be selected along with the proper tube and the transformer of the proper design to give the desired output pulse.

PRACTICAL CIRCUITS

While the entire discussion of the design and operation of the single swing blocking oscillator has been given with reference to a circuit wherein plate-to-grid feedback is employed, this is not the only feedback method available.(19) Figure XXII illustrates a circuit using plate-to-cathode feedback; Figure XXIII, cathode-to-grid feedback; Figure XXIV, plate-to-cathode-to-grid feedback. The operation of all of these circuit arrangements differ somewhat and their output waveforms differ. They do fall within the definition of the single swing blocking oscillator and are used in certain special applications. They are shown here to bring out the circuit variations of the blocking oscillator. The circuit which is most commonly used is that about which this paper has centered---the plate-to-grid feedback circuit.

APPLICATIONS

The extreme versatility of the plate-to-grid feedback circuit is illustrated in Figure XXV.(19) From this circuit three types of output are available: 1) a "voltage" pulse may be taken from points P_1 and P_2, 2) a current pulse, that is, an IR drop, may be taken across resistors in the plate, grid or cathode circuits, 3) the self-bias voltage may be taken from P_2.

In view of the versatility of this circuit, it is not surprising that it has found wide use. Perhaps the most common use of this circuit is its use in the ordinary television receiver as an impulse generator in the deflection voltage generator circuit.(17) In this application the free running blocking oscillator is synchronized and produces a sharp pulse which triggers a vacuum tube sawtooth voltage generator. This circuit is shown in Figure XXVI.

Other applications of the single swing blocking oscillator are shown in Figures XXVII through XXX. While these are by no means all the uses of the single swing blocking oscillator they are sufficient to set forth the importance of this useful device.

CONCLUSION

The qualitative explanation of the operation of the blocking oscillator has been carried out from the

definition of the blocking oscillator as a feedback oscillator with intermittent operation. According to this definition two types of blocking oscillators exist, the single and multiple swing types. The operation of the multiple swing type was qualitatively explained entirely by extension from that of the normal feedback oscillator. Also, the design of the multiple swing type was given by analogy with that of the normal feedback oscillator.

The explanation of the operation of the single swing blocking oscillator was closely related to that of the multiple swing type. But the complete explanation could not be given without resorting to simplified circuit analysis developed to explain experimentally observed facts. A theoretical analysis based on simplified theoretical mathematics (pg. 26) was given to indicate the mathematical difficulties involved and the necessity for considering experimental results.

Based primarily upon the observed wave shape the semi-mathematical theory given (pg. 33) explains the operation of the single swing type without reference to the wave shape or operation of the multiple swing type. It thus completes the explanation of the operation. In addition, the circuit parameters which contribute definition of the blocking oscillator as a feedback oscillator with intermittent operation. According to this definition two types of blocking oscillators exist, the single and multiple swing types. The operation of the multiple swing type was qualitatively explained entirely by extension from that of the normal feedback oscillator. Also, the design of the multiple swing type was given by analogy with that of the normal feedback oscillator.

The explanation of the operation of the single swing blocking oscillator was closely related to that of the multiple swing type. But the complete explanation could not be given without resorting to simplified circuit analysis developed to explain experimentally observed facts. A treatment analysis based on simplified theoretical mathematics (pg. 88) was given to indicate the mathematical difficulties involved and the necessity for considering experimental results.

Based primarily on the observed wave shape the semi-theoretical theory given (pg. 73) explains the operation of the single swing type without reference to the wave shape or operation of the multiple swing type. It gave conclusions the explanation of the operation. In addition, the circuit parameters which contribute to the wave shape are quantitatively introduced. From this, direct design information can be obtained. So, while completing the qualitative explanation of the operation, this mathematics brings out the effect of circuit elements upon operation.

In order to demonstrate the importance of the blocking oscillator, several applications of each type were given.

It appears to the writer that the most complete qualitative explanation of the operation of the single swing blocking oscillator is a combination of that evolving from the normal feedback oscillator (see "Qualitative Resumé of Operation") and that based upon experiment (see "Semi-Mathematical Theory of Operation Based Upon Experiment").

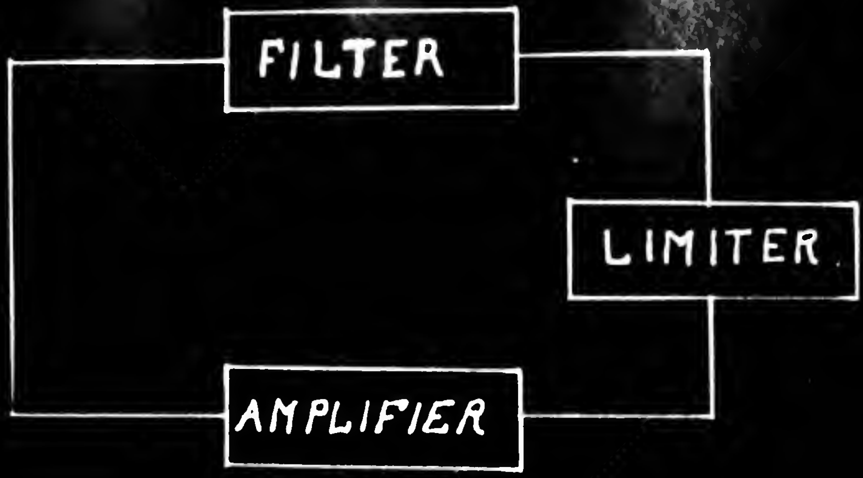


FIG I

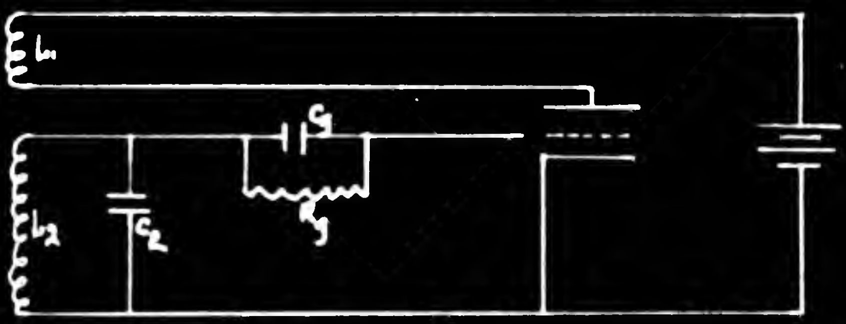


FIG II

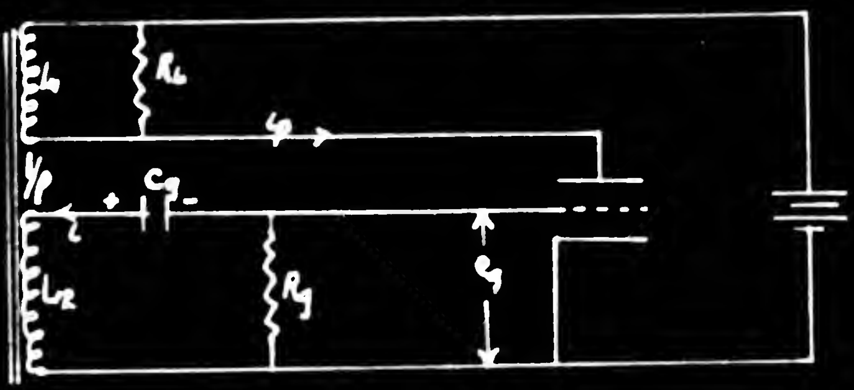


FIG IIA

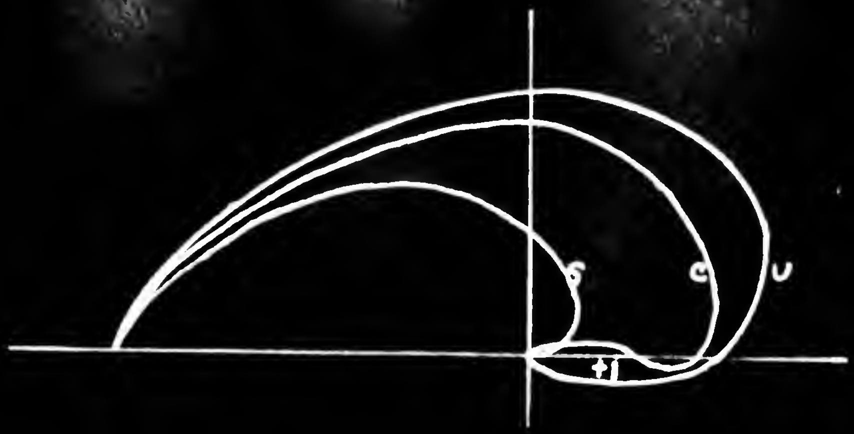


FIG III

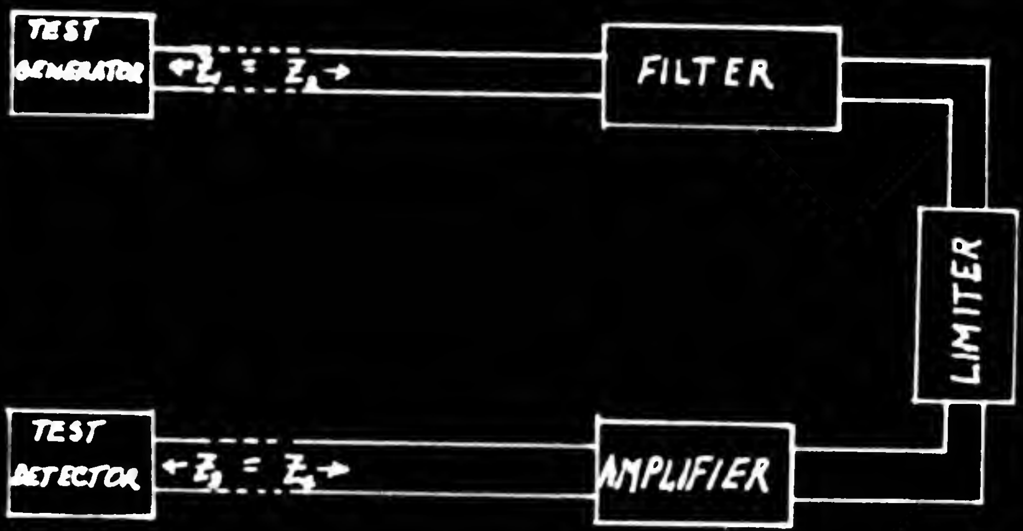
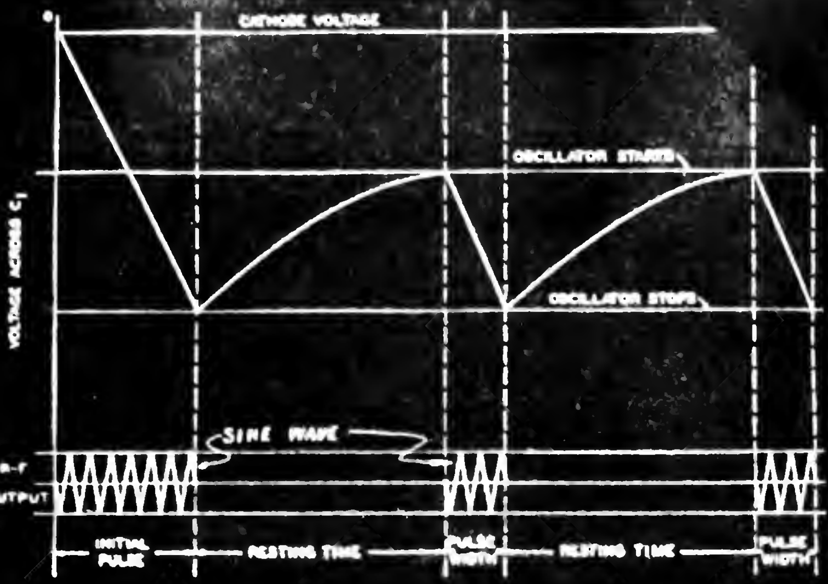
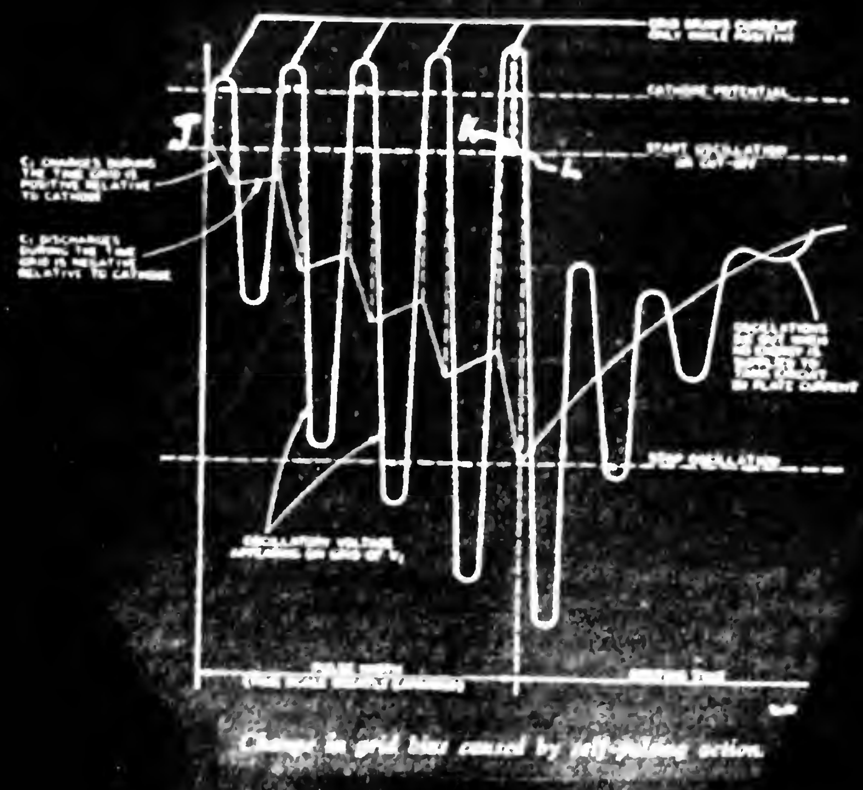


FIG IV



Intermittent pulses of r-f energy produced by self-pulsing action.

FIG V



Change in grid bias caused by self-pulsing action.

FIG VI

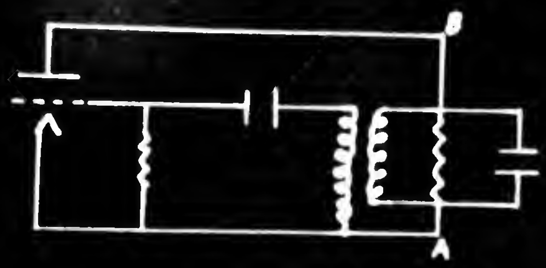


FIG VII

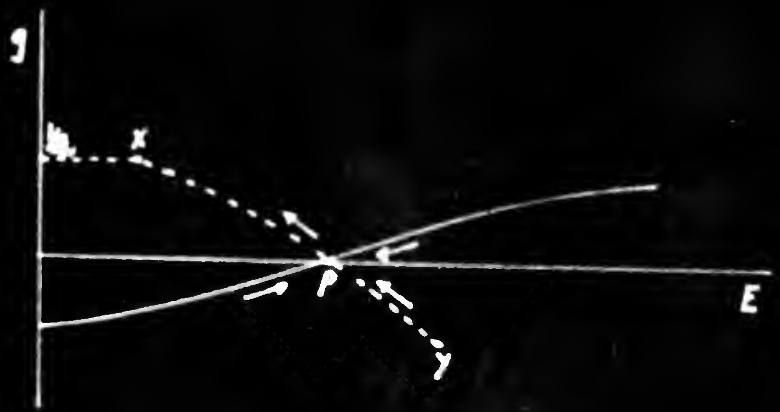


FIG VIII

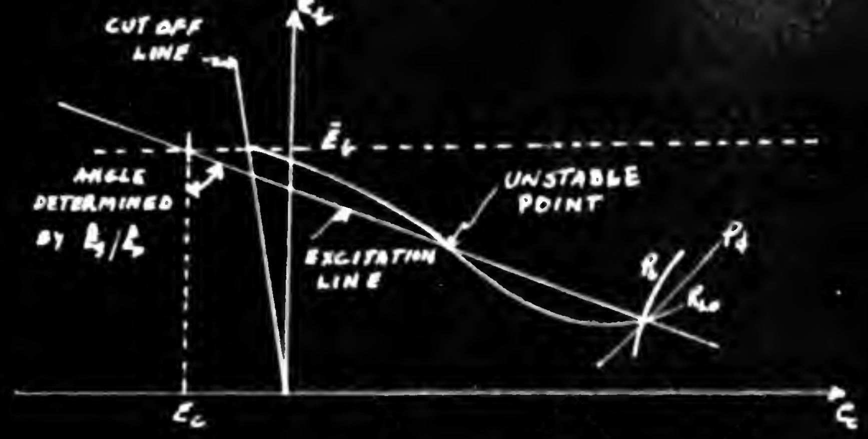

CUT OFF LINE
ANGLE DETERMINED BY
UNSTABLE POINT
EXCITATION LINE
POINT

FIG IX

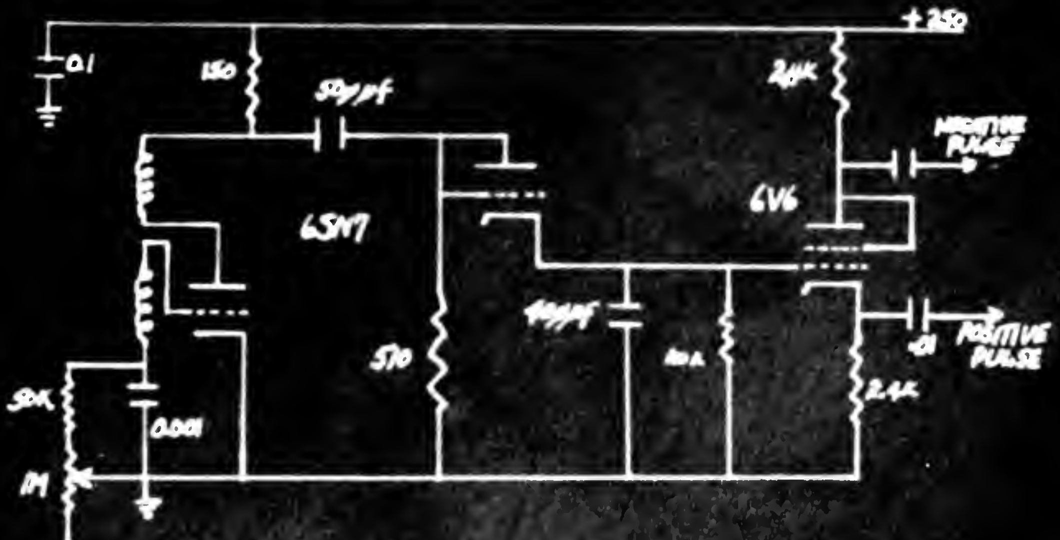

+250
.01
150
50μμf
6SN7
6V6
NEGATIVE PULSE
POSITIVE PULSE
510
2.4K
0.001
50K
1M

FIG X

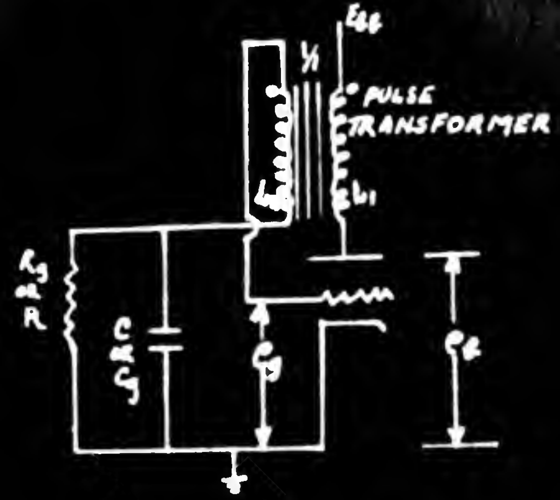


FIG XI

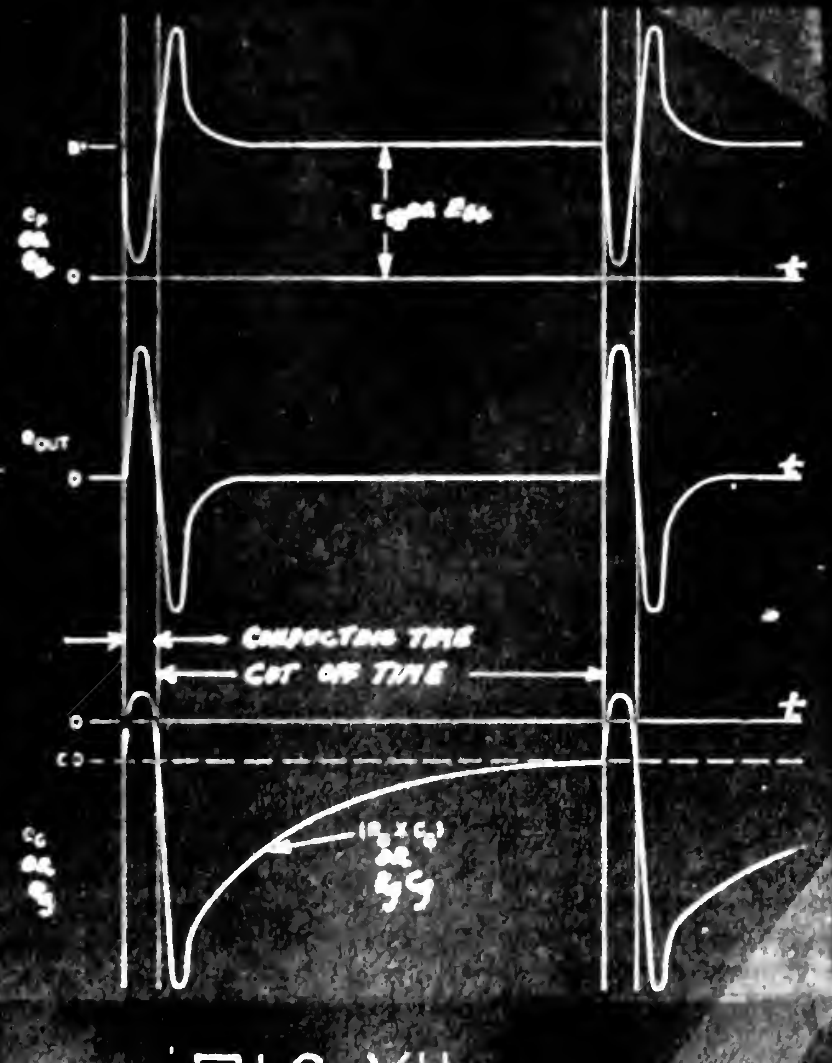


FIG XII

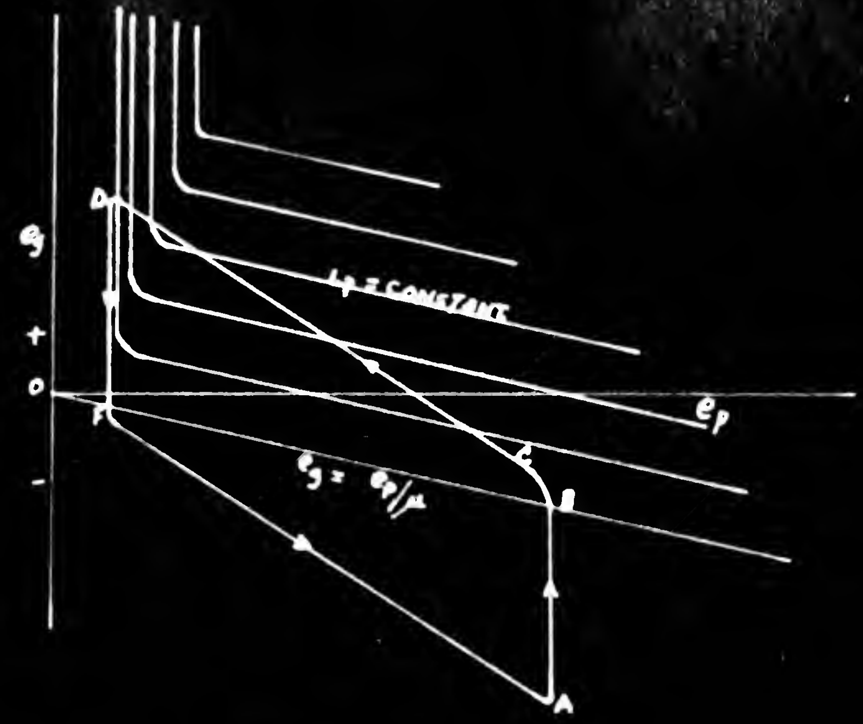


FIG XIII

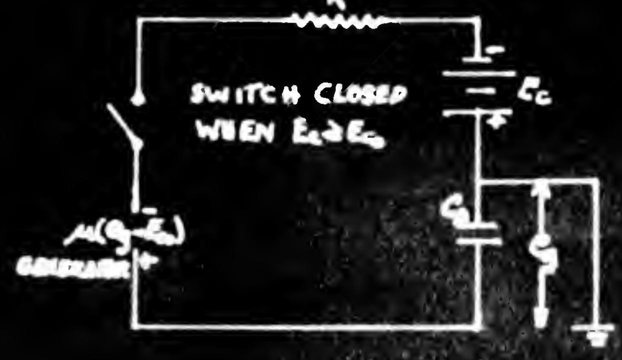


FIG XIV

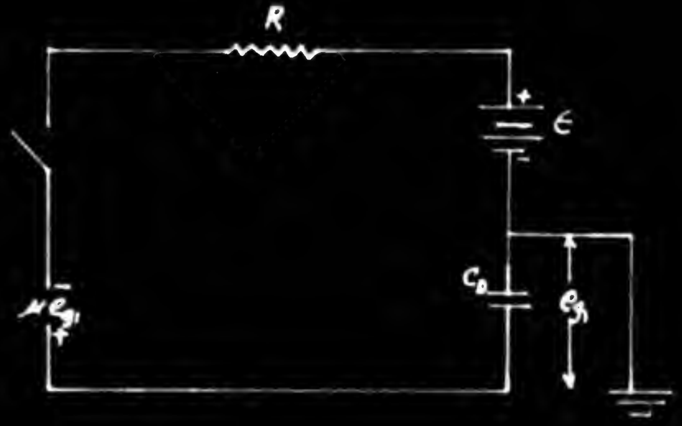


FIG XV

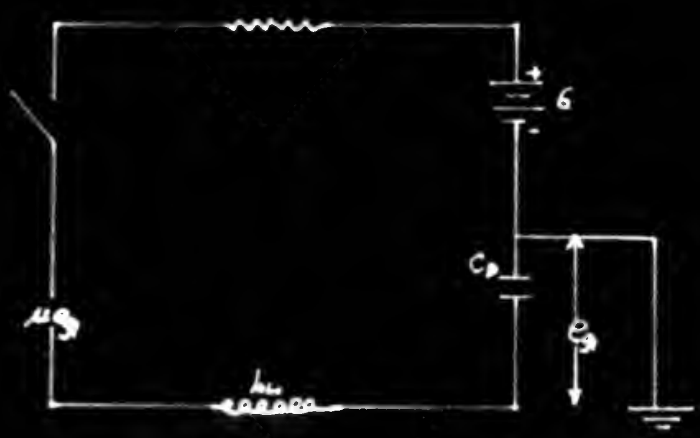


FIG XVI

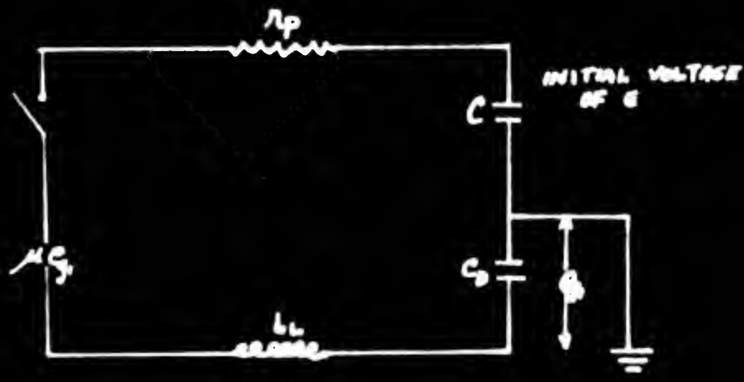


FIG XVII

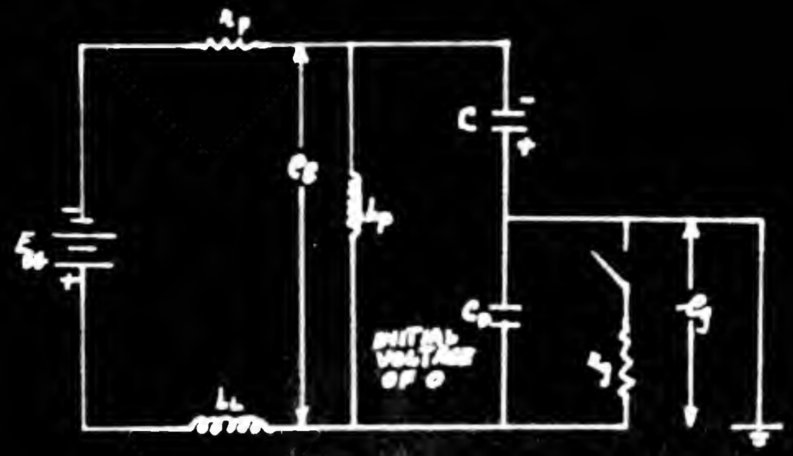


FIG XVIII

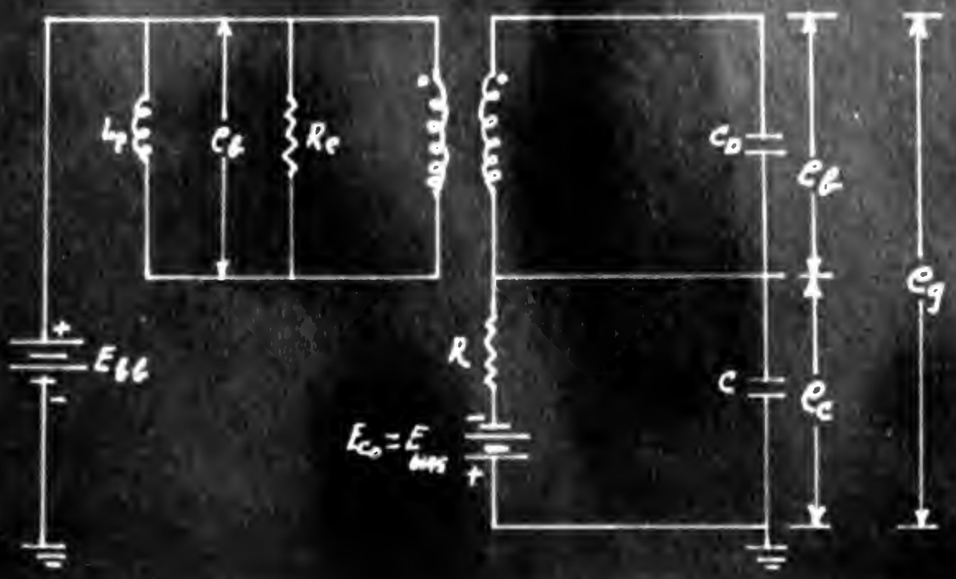
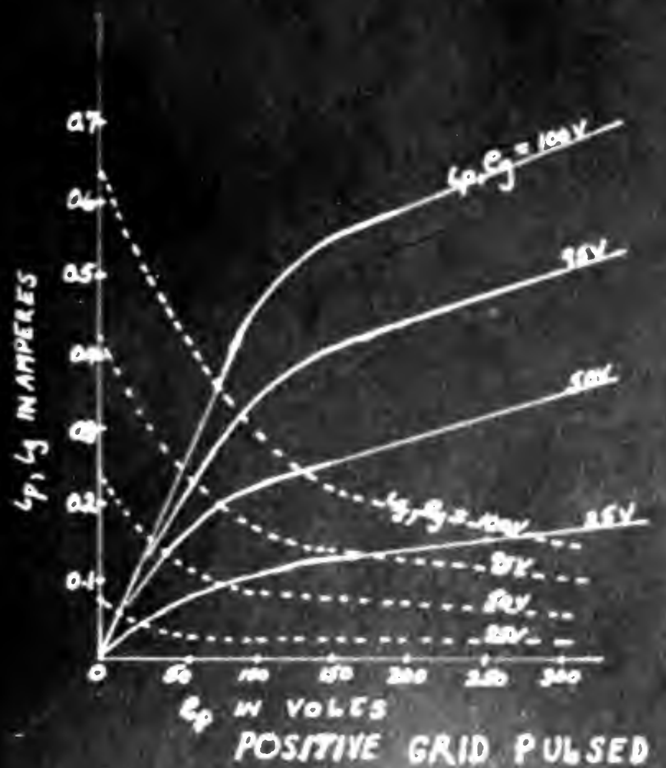
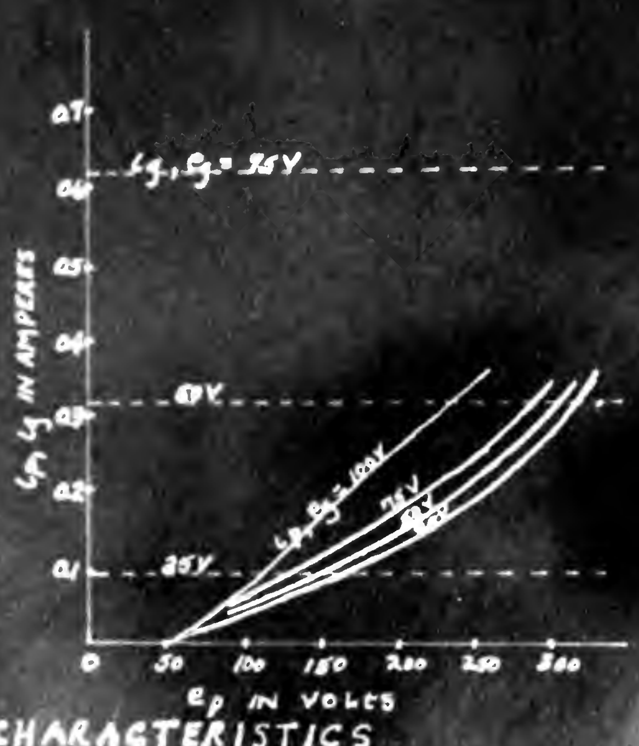


FIG XIX





POSITIVE GRID PULSED CHARACTERISTICS

FIG XX

FIG XXI

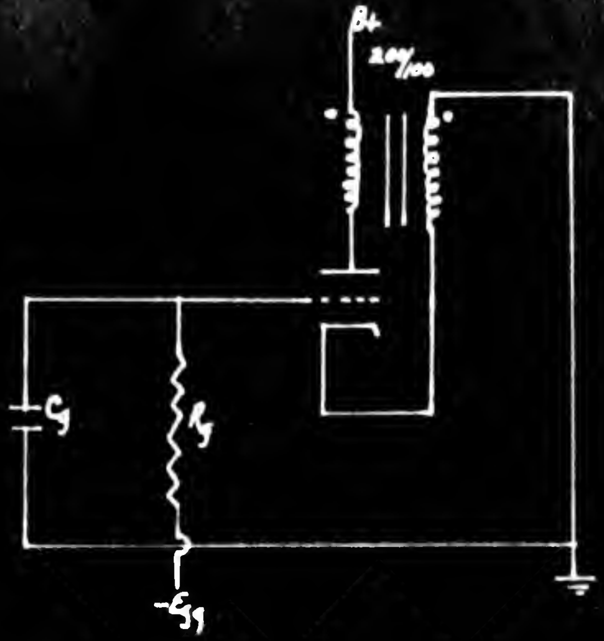


FIG XXII

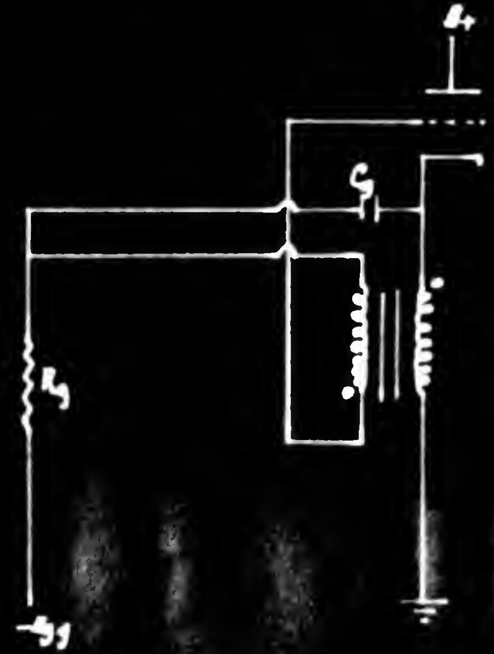


FIG XXIII

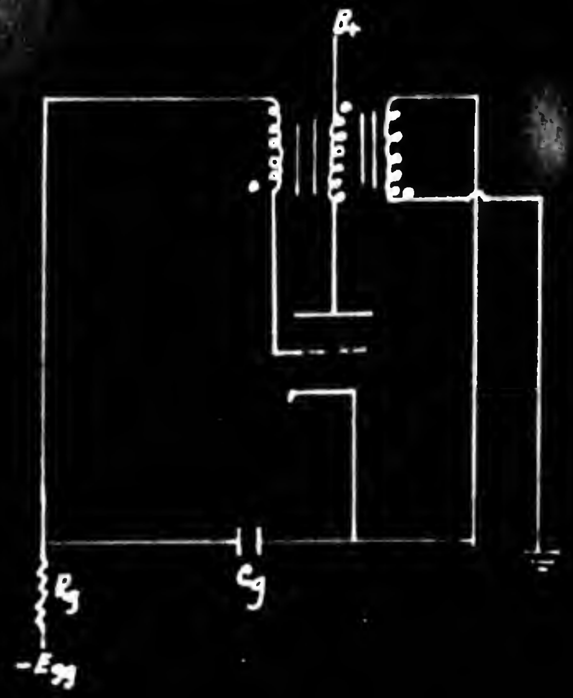


FIG XXIV

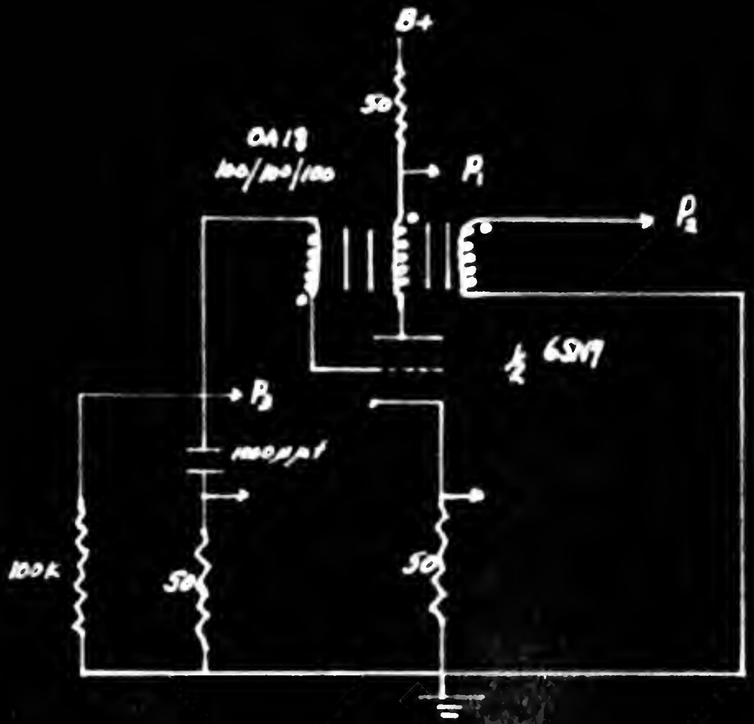


FIG XXV

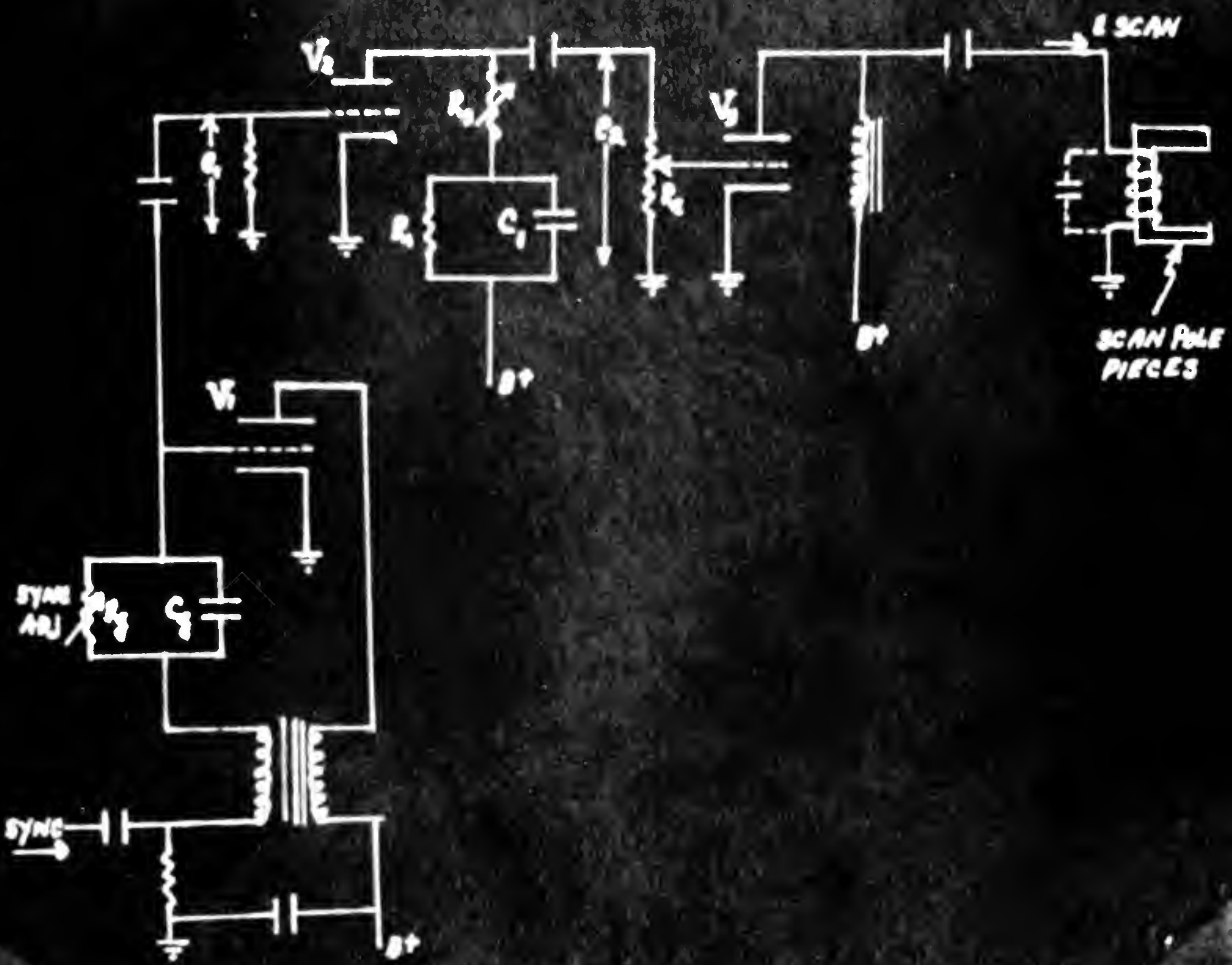
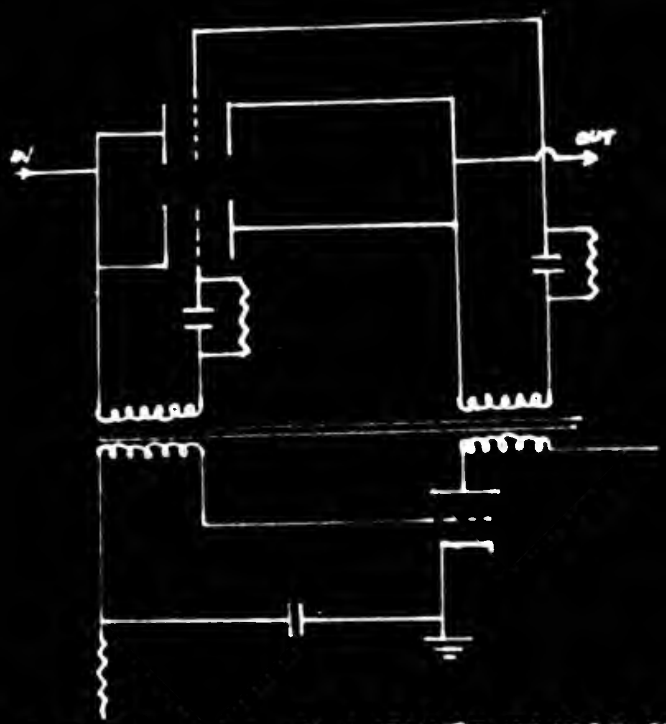


FIG XXVI

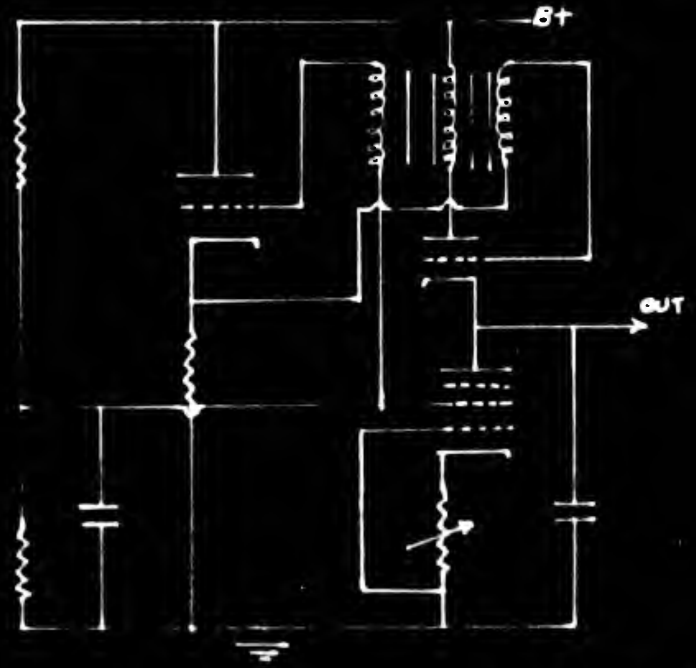


BLOCKING OSC TO ACTUATE TRIODE SWITCH

FIG XXVII

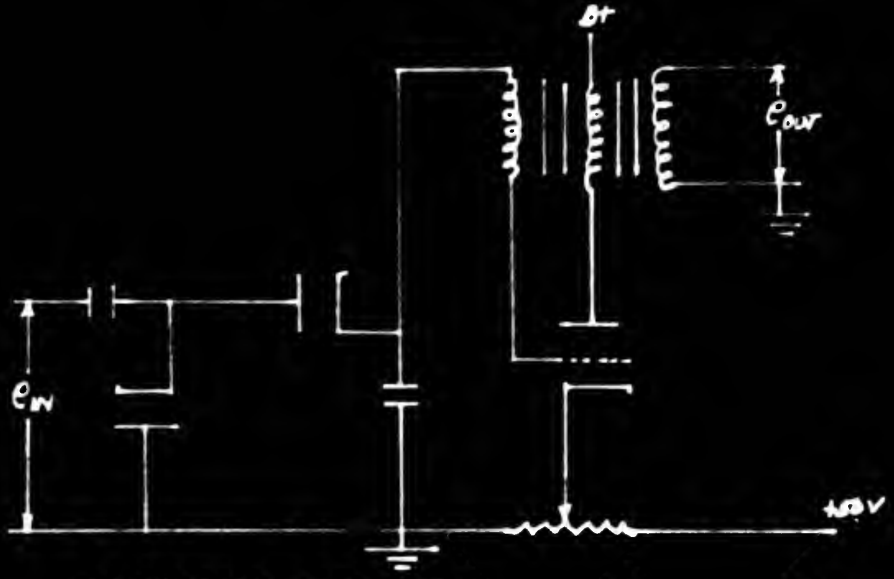
BLOCKING OSC TO ACTUATE DIODE SWITCH

FIG XXVIII



FREE RUNNING NEGATIVE SAWTOOTH GENERATOR

FIG XXIX



BLOCKING OSC IN COUNTER CIRCUIT

FIG XXX

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VITA

Claude Herman Welch was born at Holder, Louisiana on October 31, 1917. He graduated from high school at Forest Hill, Louisiana in 1935. In February 1936 he enlisted as a Private in the United States Marine Corps. While serving aboard the U.S.S. Indianapolis in the United States Fleet he successfully passed the entrance examination to the U.S. Naval Academy and entered the Academy in July 1937. He graduated from the Naval Academy in 1941 with a Bachelors Degree in Engineering, and was commissioned a Second Lieutenant in the Marine Corps. He was subsequently promoted to the rank of Major.

In the fall of 1941 he entered the Army Signal Schools at Fort Monmouth, New Jersey and received training in radio and radar. Emerging from Monmouth in May 1942 as one of the first ten Marine officers to be trained in the installation, operation and maintenance of radar he was immediately assigned overseas duty. He installed and operated search radars at three separate locations over a period of eight months, and, for work on one of these, was specially commended by the Secretary of Navy.

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In 1943 he returned to the United States and entered flight training in the Naval Aviation organization. After receiving his Navy wings in May 1944, he received further training in operational type aircraft before going overseas as a Marine fighter pilot. From January 1945 until April 1946 he served in the Palau Islands and Okinawa.

In April 1946 he again returned to the United States and was ordered to the Electronics Division, Bureau of Aeronautics, Navy Department and there served until July 1947 when he entered the Naval Postgraduate School, Annapolis, Maryland.

Following a year at the Naval Postgraduate School he was admitted to the Graduate School, Department of Electrical Engineering, Johns Hopkins University in September 1948. He has been a full time student at the Johns Hopkins from that time to the present, May 1950.

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